SOLID STATE ELECTRIC POWER SUPPORT EQUIPMENT FOR B-1B HANGAR MAINTENANCE

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Two commercially available solid state frequency converters (90 KVA, 60 Hertz to 400 Hertz, 3 phase WYE systems) were evaluated in a field test to determine if their electrical power output quality was acceptable for U.S. Air Force systems. Load bank and aircraft testing determined that the solid state frequency converters are capable of producing acceptable power. The off-the-shelf units will require some modifications to reduce the harmonic distortion and to improve the voltage regulation in order to meet current specifications (MIL-M-4803D, General Requirements for Motor-Generators). Specifications for solid state frequency conversion equipment are being drafted by the item manager and will be similar to MIL-M-4803I The frequency regualtion of the solid state frequency converter was exceptionally good. In addition, the wide power factor operating range, easy access for maintenance, and anticipatec improvement in the mean time between failure continue to make this technology attractive as an alternative for providing 400 Hertz facility power for aircraft use.

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APPROVED: Specific action by organizations or units will not be taken as a result of this report unless requested by HQ SAC under separate cover.

FOR THE COMMANDER IN CHIEF

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Director of Aircraft Maintenance
DCS/Logistics
Headquarters Strategic Air Command

SUMMARY

Two commercially available solid state frequency converters (90 KVA, 60 Hertz to 400 Hertz, 3 phase WYE systems) were evaluated in a field test to determine if their electrical power output quality was acceptable for U.S. Air Force systems. Load bank and aircraft testing determined that the solid state frequency converters are capable of producing acceptable power. The off-the-shelf units will require some modifications to reduce the harmonic distortion and to improve the voltage regulation in order to meet current specifications (MIL-M-4803D, General Requirements for Motor-Generators). Specifications for solid state frequency conversion equipment are being drafted by the item manager and will be similar to MIL-M-4803D. The frequency regulation of the solid state frequency converters was exceptionally good. In addition, the wide power factor operating range, easy access for maintenance, and anticipated improvement in the mean time between failure continue to make this technology attractive as an alternative for providing 400 Hertz facility power for aircraft use.

I. INTRODUCTION

1.1 **PURPOSE:** The purpose of this engineering project was to investigate and document the performance of 230 volt, 400 Hz solid state frequency converters for possible U.S. Air Force use.

1.2. **BACKGROUND:** HQ SAC/LGSE and SM-ALC/MMI were approached by two manufacturers of solid state frequency conversion equipment with offers to provide articles for test at no cost to the government. This technology has the promise of providing high quality power with reduced operating and maintenance cost. The initial cost of the solid state frequency converters also appears to be competitive with the motor-generator type equipment currently in the Air Force inventory. SM-ALC and both manufacturers wanted to test 230 volt, 400 hertz, three phase WYE systems since this voltage is used on the B-1B and is also expected to be used on future aircraft.

II. PROCEDURES

The objective of the test was to investigate the performance, electrical properties and construction of two solid state frequency converters. An ECU-105 motor-generator was also tested to provide control data. The following three power conversion units were tested:

(a) Article 1 was a 90 KVA, 230 volt, three phase WYE, solid state frequency converter manufactured by Jetway Division of Abex Corporation. Jetway representatives were invited to monitor the test.

(b) Article 2 was a 90 KVA, 230 volt, three phase WYE, solid state frequency converter manufactured by Controlled Systems Incorporated. Controlled Systems representatives were invited to monitor the test.

(c) Article 3 was a 75 KVA, 230 volt, three phase WYE, ECU-105 motor-generator currently in the Air Force inventory and available at Dyess AFB, Texas.

The test sequence is described below. Two series of tests were conducted. The first test sequence appraised each unit's performance on a load bank and the second applied power to an aircraft to ensure that anticipated aircraft hangar maintenance loads could be supplied by each unit.

2.1 LOAD BANK TEST -- This test sequence provided the data necessary to determine the output voltage adjustment range, voltage and frequency regulation, voltage modulation, phase voltage imbalance, total harmonic distortion, and transient voltage and frequency stability. Descriptions of these parameters are contained in appendix A. The test equipment configuration is shown in appendix B, figure 1.

(a) Allow the unit to warm-up for 10 minutes at 50 percent load.

(b) Determine the range of output voltage adjustments and the adjustment step size under no load conditions. Set the output voltage to 230 volts line to neutral.

(c) Under balanced conditions, with 1.0 power factor loads at 0, 25, 50, 75, and 100 percent of the rated load measure the:

-- Voltage (line to neutral) and current on each phase at the input panel (Fluke 8060, 801-600).

-- Voltage (line to neutral) and current on each phase at the output panel (Fluke 8060, 801-600).

-- Voltage, current, KVA, KW, KVAR, and power factor at the load end of the output cable (Dranetz 808).

-- Frequency on each phase of the output (Fluke 8060).

-- Maximum and minimum output voltage waveform peak heights on each phase in a two minute period (Sencore Oscilloscope).

-- Harmonic content of the output voltage waveform on each phase (HP-331A).

(d) Repeat step (c) with the power factor changed to 0.8 lagging.

(e) Load one phase at a time to 50 and 100 percent of the rated per phase load (power factor=1.0) and at each step measure the:

-- Voltage, current, KVA, KW, KVAR, and power factor at the load end of the output cable (Dranetz 808).

-- Harmonic content of the output voltage waveform on each phase (HP-331A).

(f) Repeat step (e) with the power factor changed to 0.8 lagging.

(g) Monitor the voltage and frequency transient response to sudden load changes with a Dranetz

606-3 Line Disturbance Analyzer. The Dranetz 606 was configured to monitor three phase, 400 Hz WYE connected power systems. The following data are recorded.

-- Slow average output voltage. This is the average output voltage over a 10 second period. Deviations greater than plus or minus 3 volts and the time the deviation occurred are printed.

-- Sag/Surge voltage. Any deviation of plus or minus three volts from the slow average output voltage was recorded. The voltage used for sag/surge measurements is the average voltage over 8 periods of a 400 Hz signal. The duration of the sag/surge is recorded as the number of cycles where the 8 period average voltage remained three volts or more away from the slow average output voltage. The time the deviation started is also printed.

-- Impulse voltage. Whenever a "spike" or impulse voltage (duration of 0.5 to 800 microseconds) differed from the anticipated instantaneous voltage by plus or minus 50 volts, the time, phase and peak voltage deviation from the AC line voltage were printed.

-- Output frequency deviation. Whenever the one second average frequency deviated more than plus or minus 4 Hz from the last printed value (nominally 400 Hz), the frequency and time of occurrence were printed.

First, the generator was subjected to a step decrease in load from 50 percent load with a 1.0 power factor to no load. After the voltage and frequency stabilized, the 50 percent, 1.0 power factor load was reapplied as a step function.

Then, the load was increased to 100 percent of the rated output with a 1.0 power factor. The generator was then subjected to a step decrease from full to no load. After the voltage and frequency stabilized, the 100 percent, 1.0 power factor load was reapplied as a step function.

(h) Repeat step (g) with a 0.8 power factor.

2.2 **AIRCRAFT TEST** -- This test examined the ability of each unit to supply power to an aircraft. The power units were instrumented with a Dranetz 808 Power Demand Analyzer and a Dranetz 606-3 Power Line Disturbance Analyzer connected to the end of the output cable through the remote sensing leads. The equipment configuration is shown in appendix B, figure 2. The test steps consisted of:

(a) Applying power to the aircraft in the basic power-on configuration, load management mode 4 (LM 4). All switches were in the post flight configuration.

(b) Turn-on the fuel transfer pumps.

(c) Turn-on the fuel boost pumps by placing the engine start switches to the run position.

(d) Return all switches their original position and remove external power from the aircraft.

III. RESULTS AND DISCUSSION

3.1 **LOAD BANK TEST** -- All of the data collected during this portion of the test are tabulated in appendix C and F. Several general comments about the test data and procedures are required before proceeding into a detailed discussion of the data.

The test was started in Dyess AFB Aerospace Ground Equipment (AGE) facility but had to be terminated and restarted in hangar 5020. The AGE facility power was rated as 480 V line to line; but when measured, the voltage was found to be 419 V line to line. Since the manufacturers had been informed that the input voltage would be 480 V, their equipments were not configured for 419 V input. Since Jetway had a variable tap input transformer on their unit they could, with minor rewiring, handle the lower voltage. However, since the CSI unit did not have variable input capability the testing was moved to another facility where the no load input voltage was 495 V line to line. At full load, the input voltage only dropped to 481 V line to line. All of the data obtained prior to moving to the new facility is not presented in the data tables. Thus, the test data was collected with virtually identical input voltages, loads and test equipment. A different ECU-105 was used for the test conducted in hangar 5020.

When a different ECU-105 was used for testing in hangar 5020; discrepancies in the data led to the discovery of a problem with the first ECU-105. The new ECU-105 used in the AGE shop test required maintenance since the input power required to operate at no load approached 30 KVA. This unit was later found to be "stuck in the start mode". The ECU-105 appeared to operate normally, and the problem would probably not have been discovered in normal use.

The three units tested provided the opportunity to examine different mounting options. The ECU-105 was skid mounted while the Jetway unit was trailer mounted and the CSI unit was a floor/wall mountable unit. Both CSI and Jetway indicated that their companies had floor and trailer mountable versions of their equipment. SAC prefers that the mounting of the units be an option decided at the time of purchase. Some applications can use the floor/wall mounting system to get the equipment out of the way while trailer mounting provides the flexibility to reposition the units in hangars where they are most needed. Trailer mounted units also help to reduce the length of 400 Hz power output cables.

The output voltage adjustment on all test articles was continuous over at least a 40 volt range. The Jetway unit voltage adjustment was not easily accessible and required a circuit card to be removed. This needs to be changed and steps were taken to modify this feature during the test. The CSI voltage adjustment consisted of an easily turned knob on the exterior control panel of the unit. This should be changed to require a screwdriver in order to prevent unintentional changes to the output voltage. ECU-105 voltage adjustment could be accomplished with a screwdriver and was accessible on the control panel.

The remote sensing cable, manufactured by Burton Electric worked well. Voltage measurements at the load bank and at the remote sensing lead terminations were within 0.5 volts of each other. These leads were used to measure the voltage at the end of the output cable.

The results are presented in relation the the rated output of the test article. Both solid state converters were rated at 90 KVA while the ECU-105 is rated at 60 KW or 75 KVA at a 0.8 power factor. There were no power factor restrictions on the solid state frequency converters and the maximum KW rating was also 90 KW. In order to keep any comparison of data as fair as possible, the loads are expressed as a percentage of the rated load. The real power limit of the solid state converters was treated as if the rated output in KVA was at a 0.8 power factor. Thus, the base for the solid state frequency converter real power load percentages is 72 KW (90KVA * 0.8). The loads applied to each unit were matched as well as possible.

3.1.1 <u>Balanced three phase loads</u> -- Each load was balanced as well as possible given the capabilities of the load bank. In the discussion that follows, references to 1.0 and 0.8 power factors should be understood to be the nominal values that were attempted to be matched. The same situation applies to the term balanced three phase loads. No effort was spared to obtain equal currents in each phase; however, some imbalance existed in all loads. Failure to obtain well balanced loads will most seriously affect the phase voltage imbalance. If the currents in the output cable are unequal, the voltage drops in each phase will be unequal causing the measured phase voltage imbalance to be higher than if the load was perfectly balanced. The potential problem of unbalanced loads did not seriously affect the phase voltage imbalance as discussed further in section 3.1.1.2. The other calculated parameters, voltage regulation, frequency regulation and voltage modulation, are less sensitive to slightly unbalanced conditions since these parameters are based on either averages or single phase data. The results obtained from balanced three phase loads are summarized in table 1 for all three test articles. The following discussion will be based on the data summarized in table 1 and found in appendix C.

TABLE 1: Data Summary for Balanced Three Phase Loads at 1.0 and 0.8 Power Factors (pf)

		NOMINAL 1.0 pf					NOMINAL 0.8 pf			
JETWAY SOLID STATE FREQUENCY CONVERTER DATA SUMMARY	LOAD %	1.06	24.08	47.41	70.41	98.68	24.17	49.79	76.52	99.54
	PF	0.90	0.99	0.99	0.99	0.99	0.83	0.80	0.83	0.88
	EFFICIENCY%	0.89	27.87	32.38	35.57	39.10	33.51	42.14	46.01	46.07
	PVI %	0.16	0.22	0.24	0.26	0.25	0.22	0.81	0.42	0.55
	Vreg %	0.00	0.42	0.48	0.21	1.61	1.57	1.01	1.10	1.89
	Freg %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Avg Vmod %	0.12	0.10	0.15	0.15	0.12	0.10	0.17	0.12	0.17
	Avg THD	1.32		1.74	1.88	1.74		1.92		1.92
CSI SOLID STATE FREQUENCY CONVERTER DATA SUMMARY	LOAD %	1.06	24.63	47.93	71.71	97.20	25.10	48.31	72.45	103.03
	PF	0.89	0.99	0.99	0.99	0.99	0.83	0.81	0.83	0.87
	EFFICIENCY%	12.59	25.64	32.38	32.64	35.92	33.94	38.24	43.18	44.48
	PVI %	0.12	0.07	0.07	0.09	0.09	0.43	0.81	0.16	0.43
	Vreg %	0.00	0.29	0.96	0.28	0.49	0.86	1.66	2.40	4.36
	Freg %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Avg Vmod %	1.16	1.57	0.65	1.13	0.79	1.10	0.87	0.61	0.78
	Avg THD	3.45		2.32		4.60		2.33		2.00
ECU-105 MOTOR-GENERATOR DATA SUMMARY	LOAD %	1.25	29.37	49.01	80.73	101.66	26.99	60.17	72.07	104.46
	PF	0.89	0.99	0.99	0.99	0.99	0.82	0.85	0.84	0.86
	EFFICIENCY%	5.88	24.95	38.02	48.98	54.42	33.37	53.95	57.99	64.10
	PVI %	0.07	0.06	0.19	0.43	0.22	0.17	0.57	0.15	0.34
	Vreg %	0.00	0.03	0.18	0.29	0.19	0.47	0.16	0.26	0.25
	Freg %	0.00	0.01	0.03	0.03	0.00	0.02	0.02	0.03	0.03
	Avg Vmod %	0.07	0.05	0.02	0.07	0.05	0.15	0.05	0.05	0.07
	Avg THD	0.44		0.42		0.40		0.39		0.35

3.1.1.1 Efficiency -- The efficiency data obtained during the test was not usable. In using the Fluke 8060 multimeter with the matching inductive AC current pick-up 801-600, significant errors were introduced into the data. The equipment was bench checked with short duration current pulses in an attempt to simulate the solid state frequency converter input waveform and the multimeter/probe values were found to be in error by as much as 15 percent relative to measurements made with the meter alone. The error is believed to be the result of the inductive probe acting as a highpass filter. This problem only affects the input of the solid state frequency converters since they draw current only when required to form the output sinusoid.l. Retrospectively, the input and output power flow should have been measured with watt meters and power factor meters of a type similar to that used by utility companies. in any case, the efficiency data must be neglected.

3.1.1.2 Phase voltage imbalance -- The phase voltage imbalance remained less than one percent for all balanced three phase loads at 1.0 and 0.8 power factors. The solid state frequency converters had very flat response curves for 1.0 power factor loads while the motor-generator exhibited greater data spread (See Appendix D, Figure 1). The 0.8 power factor data for all test articles showed a response curve similar to the shape of the 1.0 power factor ECU-105 response curve. Since all three test articles displayed similar curves for 0.8 power factor loads, this shape is not thought to be caused by normal data distribution. However, at this point, the shape of the curve cannot be explained.

3.1.1.3 Voltage regulation -- With 1.0 power factor loads only one data point (100% load for the Jetway test article) fell outside the desired voltage regulation limit of 1.0 percent. See Appendix D, Figure 3 for the plotted data. The data obtained for 0.8 power factor loads (See Appendix D, Figure 4) was not as favorable. Both solid state frequency converters failed to maintain the voltage regulation below 1.0 percent. The lack of adequate regulation could have been caused by readjusting the voltage regulators when the test location was changed to avoid the hangar low voltage problem previously discussed. Both output voltage and line drop compensation were adjusted by the solid state converter manufacturer's representatives when the test location changed. The adjustments were quickly made without technical data and more meticulous adjustment procedures may be all that is required to improve the regulation. After the test started, no further adjustments were allowed. If better adjustment procedures do not correct the problem, another possibility is changing the regulator design. In any case, the output voltage regulation of the solid state frequency converters will require improvement to meet the anticipated voltage regulation specification of one percent. This should not be a serious problem since numerous pieces of electrical generating equipment are capable of meeting this requirement.

3.1.1.4 Frequency regulation -- The frequency regulation of all three test articles at both 1.Ø and Ø.8 power factors (See Appendix D, Figures 5 and 6) was well within acceptable operating limits for aircraft power. The frequency regulation of the crystal controlled solid state frequency converters was perfect at all load and power factor settings.

3.1.1.5 Voltage modulation -- The maximum voltage regulation allowed under MIL-M-48Ø3D(USAF) is 1.Ø percent. The percent voltage modulation for two of the test articles (the ECU-1Ø5 and Jetway) remained under Ø.2 percent for all loads and power factors (See Appendix D, Figures 7 and 8). Voltage modulation greater than 1.Ø percent was recorded for the CSI test article under some of the load conditions. These high voltage modulation values were observed for both 1.Ø and Ø.8 power factor loads.

3.1.1.6 Total harmonic distortion -- The total harmonic distortion was unacceptable on the CSI test article and marginal on the Jetway test article in relation to the maximum of 2.Ø percent referenced in MIL-M-48Ø3D (See Appendix D, Figures 9 and 1Ø). The same limit is expected to apply to solid state frequency converters when their general requirement specification is completed. CSI literature indicates that they have a harmonic filter available as a option that will reduce the harmonic content of their output to less than 2.Ø percent.

3.1.2 <u>Single phase loads</u> -- The single phase loads tested are worst case conditions where only one phase is loaded to a percentage of the single phase'rated power (1/3 of the total rated output power) at both 1.Ø and Ø.8 power factors. This load is not expected to be encountered in normal operations, however there may be occasions when single phase motors would be operated from the three phase sources. Fault conditions could also result in somewhat similar conditions where one phase is drawing significantly higher current than the other two phases. The data obtained can be found in appendix C and is summarized in table 2. The no load data points used in the appendix D figures are obtained from the no load balanced three phase data presented previously in table 1. The following discussion is based on the data in table 2.

TABLE 2: Data Summary for Single Phase, 1.0 and 0.8 Power Factor Loads.

		NOMINAL 1.0 PF		NOMINAL 0.8 PF	
JETWAY SOLID STATE FREQUENCY CONVERTER DATA SUMMARY	LOAD %	49.91	96.61	46.05	87.11
	PF	0.99	0.99	0.78	0.89
	PVI %	1.51	4.13	5.16	8.61
	Vreg %	1.90	3.68	0.73	1.70
	Avg THD	2.29	2.97	3.27	5.02
CSI SOLID STATE FREQUENCY CONVERTER DATA SUMMARY	LOAD %	45.91	83.74	43.09	84.35
	PF	0.99	0.99	0.79	0.87
	PVI %	4.63	8.32	9.02	14.13
	Vreg %	0.23	0.26	0.41	0.62
	Avg THD	3.68	5.03	4.33	? FQ FLUX
ECU-105 MOTOR-GENERATOR DATA SUMMARY	LOAD %	51.63	92.02	55.31	89.87
	PF	0.99	0.99	0.88	0.87
	PVI %	1.65	3.18	2.57	4.69
	Vreg %	1.55	2.88	2.01	3.94
	Avg THD	0.49	0.67	0.51	0.67

3.1.2.1 Phase voltage imbalance -- All three test articles failed to remain within the 3.0 percent phase imbalance upper limit as specified in MIL-M-4803D, paragraph 3.7.9, when the maximum single phase load was applied. The data for 1.0 and 0.8 power factor loads are plotted in appendix D, figures 11 and 12. With this severe single phase load, maintaining the phase voltage imbalance would probably require circuitry that could independently sense and control each phase voltage. This requirement, due to the extreme nature of the load, warrants reconsideration when the specifications for solid state frequency conversion equipment are finalized.

3.1.2.2 Voltage Regulation -- Voltage regulation requirements for single phase loads are not specifically stated in MIL-M-4803D, but the specification does call for the output voltage to be controlled to within 1.0 percent "throughout the power factor and load range" in paragraph 3.7.4. Appendix D, figures 13 and 14, show that the only the CSI test article achieved this level

of performance. This was not expected since the CSI test article did not perform this well for the balanced three phase loads. This performance is also attributed to adjustment of the voltage regulator as was the poor performance described in paragraph 3.3.3.2. These findings support the opinion that the observed voltage regulation is not a serious problem for any of the test articles.

3.1.1.3 Total harmonic distortion -- The total harmonic distortion for single phase loads is presented in appendix D, figures 15 and 16. The total harmonic distortion limit of 2.0 percent as contained in MIL-M-4803D, paragraph 3.7.7, does not clearly apply to single phase loads. Only the ECU-105 test article maintained the harmonic content within 1.0 percent for all single phase loads. The CSI test article had a frequency flux at the nominal 100 percent load, 0.8 power factor data point, that prevented obtaining harmonic content data.

3.1.3 <u>Load bank shock loads</u> -- All three test articles were shock loaded and unloaded at nominal loads of 50 percent and 100 percent of the rated output at both 1.0 and 0.8 power factors. The actual shock loads are documented in appendix E and the results are shown in table 3.

TABLE 3. Shock Load Transient Voltage and Duration Summary

LOAD	PF	SHOCK	JETWAY MAXIMUM SAG/SURGE VOLTAGE DEVIATION	JETWAY TOTAL RECOVERY TIME(SEC)	JETWAY TYPE	CSI MAXIMUM SAG/SURGE VOLTAGE DEVIATION	CSI TOTAL RECOVERY TIME(SEC)	CSI TYPE	ECU-105 MAXIMUM SAG/SURGE VOLTAGE DEVIATION	ECU-105 TOTAL RECOVERY TIME(SEC)	ECU-105 TYPE
50 %	1.0	ON	-16	0.04	UD	-8	0.02	OD	NR	--	
	1.0	OFF	32	0.18	OD	8	0.06	OD	NR	--	
	0.8	ON	-12	0.04	UD	-12	0.20	OD	-12	0.11	OD
	0.8	OFF	34	0.20	OD	12	0.94	OD	16	0.12	OD
100 %	1.0	ON	-30	0.10	UD	-10	0.04	OD	-8	0.12	OD
	1.0	OFF	50	0.34	OD	12	0.08	OD	10	0.24	OD
	0.8	ON	-36	0.10	UD	-14	1.13	OD	-28	0.25	OD
	0.8	OFF	66	0.36	OD	26	2.14	OD	28	0.42	OD

NR = no recorded transients OD = overdamped UD = underdamped

The data in table 3 is derived from Dranetz 606-3 Line Disturbance Analyzer recorded deviations. Presently, no equivalent to MIL-STD-704D, Aircraft Electric Power Characteristics, exists for 230 volt systems. However, if the same time and voltage deviation limits as shown in MIL-STD-704D, figure 5, are transposed to a 230 volt steady state limit, a possible reference is obtained. This 230 volt based, AC voltage transient response envelope is shown in appendix F, figure 1. An oscillograph is required to precisely determine if the transient response remains within the appendix F, figure 1 envelope and the Dranetz 606-3 simply cannot provide the data required for an exact determination of the transient response. Since the rise time to the peak voltage is not known, it is not possible to develop a second order mathematical model of the response. In order to make a reasonable determination as to whether the envelope is broached, some rather broad assumptions must be made. Assuming that the highest voltage deviation occurs at the onset of the transient and that the voltage decays exponentially, returning to the original steady state value at the recovery time shown in table 2, a first order model can be derived.

First, define tau as :

$$\text{tau} = \frac{\text{Total Recovery Time}}{4}$$

and the equation:

$$V = 230 + Ae^{(-t/tau)}$$

where V is the instantaneous voltage at time t and A is the signed magnitude of the maximum voltage deviation. This equation was utilized to develop the possible response curves for the test articles contained in appendix F, figures 2 through 7. The limits displayed in appendix F, figure 1, are also displayed on the other figures.

The calculated response curves for the Jetway test articles are shown in appendix F, figures 2 and 3. The unit failed to respond fast enough to prevent the voltage from exceeding the limits for the 100 percent sudden load removal. The voltage response to the other shock loads essentially (a few data points did not) remained within the voltage limits of appendix F, figure 1.

The calculated response curve for the CSI test article are shown in appendix F, figures 4 and 5. None of the calculated response curves exceeded the limits when 1.0 power factor loads were applied and removed. The response seen with 0.8 power factor loads had small magnitude deviations, but the long response time caused the calculated response curves to exceed the desired limits.

The calculated response curve for the ECU-105 test article are shown in appendix F, figures 6 and 7. None of the calculated response curves exceeded the limits when 1.0 power factor loads were applied and removed. With 0.8 power factor loads, only the 100 percent shock load calculated response curves went out of the limits.

The mathematically generated data basically confirm that the voltage response needs to be improved for the voltage to remain in the desired limits when a 100 percent shock load is applied or removed. The calculated data also show that, for the normally encountered case where the shock load represents less than 50 percent of the units rated output, the voltage limits are essentially maintained except for some 0.8 power factor loads.

3.2 AIRCRAFT POWER-ON TEST RESULTS

The aircraft test was significantly less demanding than the load bank test. The shocks were not as great and the overall loads did not push the operating limits of the test articles. Only the Jetway and ECU-105 test articles were applied to the aircraft, B-1B #050. The CSI test article was not included in this portion of the test due to the high harmonic content and voltage modulation on their standard unit. Also, in keeping with the purpose of the test to document the feasibility of solid state frequency conversion technology for Air Force aircraft power generation, one solid state frequency converter could provide the required data.

When power was applied to the aircraft in the basic LM-4 configuration, the power consumption was 7.9 KVA at a 0.99 power factor. No transients were observed with either test article when this load was applied. Next, the fuel transfer pumps were turned on increasing the load to 27.5 KVA at a 0.88 lagging power factor. The Jetway voltage deviated slightly from the steady state value of 228 volts on each phase. Both the A and C phase voltage climbed to 236 volt and damped out in 0.06 seconds while the B phase voltage climbed to 234 volts for 0.04 seconds. The Jetway voltage control appeared overdamped in this situation since no oscillations were recorded. The ECU-105 steady state voltages on A, B and C phase were 232, 232 and 230 volts respectively. The ECU-105 voltage transients oscillated between the values of 222 volts and 236 volts for 0.4 seconds before damping out to the steady state conditions. The time required for each half cycle (time between consecutive steady state crossings) was approximately 0.08 seconds. The main fuel boost pumps were then energized by placing the engine start switches in the run position thus increasing the electrical load to 42.1 KVA at a 0.84 lagging power factor. No transients were recorded for the Jetway test article. The ECU-105 B phase voltage sagged to 224 volts for 0.04 seconds. When the loads were removed by first turning off the fuel transfer pumps followed by the fuel boost pumps, no additional voltage transients were recorded. The aircraft accepted the electrical power from both the Jetway and ECU-105 test articles and the routine maintenance task of pressurizing the fuel manifolds was completed without any problems.

IV. CONCLUSIONS

The solid state frequency converters were found to provide acceptable power. The frequency regulation was excellent, but the voltage regulation and total harmonic distortion will need improvement before solid state frequency converters can replace motor-generators. Procurement specifications being prepared by SM-ALC/MMIEC address the problems observed during this engineering project. Power generating equipment built to meet the SM-ALC specification will have power quality equivalent to motor-generators. The two off-the-shelf converters tested should be able to meet the final procurement specification with relatively minor modifications. The anticipated improvement in mean-time-between failures, reduced time to repair, and unlimited power factor range make solid state frequency converters a viable option for replacing motor-generators. As the aircraft load power factors become more reactive, the unlimited power factor range will become more important.

IV. RECOMMENDATION

HQ SAC/LGME recommends that:

a. AFLC SM-ALC/MMI release procurement specifications and stock list solid state frequency converters.

b. HQ SAC/LGSE arrange to purchase five stock listed solid state frequency converters as replacements for condemned motor-generators, providing the projected life cycle cost is favorable.

c. HQ SAC/LGSE, with LGME assistance as required, inspect the initial solid state frequency converters and monitor their performance during the first year of operation. This would ensure documentation and resolution should unforeseen problems develop.

d. Contracts include warranty provisions that specify 20,000 hours before failure.

V. DISTRIBUTION

11	HQ SAC/LGME(5)/LGMS/LGSE(2)/LGXB/LGMA/DEEQ, Offutt AFB, NE 68113-5001
5	SM-ALC/MMI/MMIK/MMIE/MMIEC(2), McClellan AFB, CA 95652-5000
1	96 BMW/MA, Dyess AFB, TX 79607-5000
1	28 BMW/MA, Ellsworth AFB, SD 57706-5000

6 Appendices

A. Electric Power Support Equipment Test Descriptions

B. Test Instrumentation

C. Load Bank Test Data

D. Figures

E. Shock Loads

F. Transient Response Figures

Appendix A

APPENDIX A

ELECTRIC POWER SUPPORT EQUIPMENT TEST DESCRIPTIONS

I. INTRODUCTION

This appendix describes the procedures and data that will be collected for tests of electrical generating equipment for aircraft use. The tests come from numerous sources and have been modified to suit the needs of HQ SAC. These tests do not constitute a initial article inspection as required by AFLC. The tests provide SAC with an abbreviated inspection/evaluation of electrical generating equipment before SAC has to operate the equipment under field conditions.

II. GENERAL SYSTEM CHECKS

2.1 VOLTAGE ADJUSTMENT -- The range of output voltage adjustment and the adjustment step size, if applicable, will be determined by adjusting the voltage regulator under no load conditions. Voltage measurements can be made at either the load or the unit end of the output cable for this test. The desired range is plus or minus ten percent of the rated output voltage.

2.2 WORKMANSHIP -- Any deficiencies in the construction or design of the unit will be noted. Examples are sharp edges, poorly fitting joints, dissimilar metal contact, metal shavings, cold or sloppy electrical connections and unreadable/unclear operating and maintenance instructions.

2.3 MAINTAINABILITY -- Although this test cannot accurately predict the mean time between failure for the test article some qualitative assessments can be made concerning the unit's maintainability. This qualitative assessment will include:

- Periodic maintenance requirements.
- Ease of access for periodic maintenance.
- Ease of access to electronic components.
- Maintenance personnel and equipment requirements.

III. TEST DESCRIPTIONS

3.1 EFFICIENCY -- The efficiency (Ef) in percent is defined as:

$$Ef = \frac{Sout}{Sin} \times (100)$$

where Sin is the total input power in thousand volt amperes (KVA) and Sout is the output power in KVA. A Fluke 8060 true RMS

multimeter with an 801-600 inductive current probe will be used to measure each phase current. The voltage of each phase (line to neutral) will also be measured with the Fluke 8060 multimeter. The value for the total power (S) for both input and output is found with the equation:

$$S=(Van*Ia)+(Vbn*Ib)+(Vcn*Ic)$$

Measurements of the efficiency shall be made at three phase balanced loads. Data points will be obtained with loads close to the 0, 25, 50, 75, and 100 percent of the rated load at a power factor of 0.80 lagging. Another set of data points will be obtained with a 1.0 power factor. Voltage measurements will be made at the input and output terminals of the unit to prevent the power cables from altering the basic unit parameters.

3.2 REGULATION -- The ability of the unit to maintain a set voltage and frequency for loads varying from 0 to the full rated output will be examined. In this test, the unit will be operated at 0, 25, 50, 75, and 100 percent of the rated output for power factors of 0.80 lagging and 1.0. The line to neutral voltage of each phase will be measured at the load end of the output cable. A Dranetz 808 power Demand Analyzer will provide the voltage, current, load and power factor data. The frequency will be measured at any convenient point on the output cable. Either an oscilloscope with digital frequency readout or a Fluke 8060 multimeter will be used to measure the output frequency.

3.2.1 <u>Voltage regulation calculation</u> -- The voltage regulation (VRx) in percent as a function of the load is calculated with the equation:

$$VRx = \frac{ABS(\ Vl-Vo\ )}{Vo} \times (100)$$

where Vo is the no load average line to neutral voltage and Vl is the average line to neutral voltage when loaded at x percent of the rated output. MIL-M-4803 requires the VR to be less than or equal to one percent at all loads.

3.2.2 <u>Frequency regulation calculation</u> --
The frequency regulation (FRx) in percent as a function of the load is calculated with the equation:

$$FRx = \frac{ABS(Fl-Fo)}{Fo} \times (100)$$

where Fo is the no load average frequency and Fl is the average frequency when loaded at x percent of the rated output.

3.3 VOLTAGE MODULATION -- The ability of the unit under test to maintain a voltage without fluctuation at a given load is

represented by the percent voltage modulation. The peak line to neutral voltage waveform value is observed for two minutes and the highest peak voltage (Vpm) and the lowest peak voltage (Vpl) are recorded. The RMS values are calculated by assuming a true sinusoidal waveform, thus:

$$Vmax = (Vpm)/(2^{.5})$$

$$Vmin = (Vpl)/(2^{.5})$$

where Vmax is the maximum RMS voltage and Vmin is the mimimum RMS voltage observed during the two minute period. The percent voltage modulation (VM) is defined as:

$$VM = \frac{Vmax-Vmin}{Vmax+Vmin} \times (100)$$

The voltage measurements will be made with balanced three phase loads and with 0.80 lagging and 1.0 power factors at each load. Test loads will include 0, 25, 50, 75, and 100 percent of the rated unit output. The percent voltage modulation should be less than one percent for all load and power factor combinations.

3.4 TRANSIENT STABILITY -- The ability of a power generating unit to respond to sudden changes in load is examined by recording the parameter of interest as a function of time. The worst case situation is to apply a full load step function to the output and to monitor the response followed by a sudden removal of the load after the unit stabilizes. This should be done for both 0.8 lagging and 1.0 power factors.

A Dranetz 606-3 Line Disturbance Analyzer was used to monitor the voltage and frequency transient response to sudden load changes. The Dranetz 606 was configured to monitor three phase, 400 Hz WYE connected power systems. The following data was recorded.

-- Slow average output voltage. This is the average output voltage over a 10 second period. Deviations greater than plus or minus 3 volts and the time the deviation occoured are printed.

-- Sag/Surge voltage. Any deviation of plus or minus three volts from the slow average output voltage was recorded. The voltage used for sag/surge measurements is the average voltage over 8 periods of a 400 Hz signal. The duration of the sag/surge is recorded as the number of cycles where the 8 period average voltage remained three volts or more away from the slow average output voltage. The time the deviation started is also printed.

-- Impulse voltage. Whenever a "spike" or impulse voltage (duration of 0.5 to 900 microseconds) differed

from the anticipated instantious voltage by plus or minus 50 volts the time, phase and peak voltage excluding the AC line voltage was printed.

-- Output frequency deviation. Whenever the one second average frequency deviated more than plus or minus 4 Hz from the last printed value (nominally 400 Hz), the frequency and time of occurrence were printed.

First, the generator was subjected to a step decrease in load from 50 percent load with a 1.0 power factor to no load. After the voltage and frequency stabilized, the 50 percent, 1.0 power factor load was reappled as a step function. Then, the load was increased to 100% of the rated load with a 1.0 power factor. The generator was then subjected to a step decrease from full to no load. After the voltage and frequency stabilized, the 100 percent, 1.0 power factor load was reappled as a step function. These steps were repeated with a 0.8 power factor

The output voltage should not deviate more than plus or minus 10.0 percent from the voltage prior to the transient. Within 0.2 seconds from the onset of the transient, the voltage should return to within 2.0 percent of the initial voltage. MIL-SPEC-704D, figure 5 contains additional guidance for 115 volt aircraft systems.

The transient frequency response is the frequency of the output signal on the desired phase measured as a function of time from the start of the step change in the load. The frequency should remain in the range 393.0 hertz to 407.0 hertz. Within 3.0 seconds the frequency should recover to 400.0 hertz plus or minus 0.5 hertz.

3.5 PHASE VOLTAGE IMBALANCE -- The phase voltage imbalance (PVI) in percent is defined as:

$$PVI = \frac{ABS(\ Vmax - Vavg\ )}{Vavg} \times (100)$$

where,

$$Vavg = \frac{Van + Vbn + Vcn}{3}$$

and Vmax is the line to neutral voltage of the phase with the largest deviation (positive or negative) from Vavg. Van, etc. represent the voltage measured from the designated phase line to the neutral line.

The PVI will be measured for a balanced three phase 0.8 lagging power factor load at 100 percent of the rated output. For these conditions, the PVI should be less than 1.0 percent. With two

phases at no load and one phase operating at 100 percent load (1/3 rated output)with a 0.8 power factor the PVI should be less than 3.0 percent.

3.6 TOTAL HARMONIC DISTORTION -- The total harmonic distortion (THD) in percent was measured directly with a HP 331A Distortion Analyzer.

Appendix B

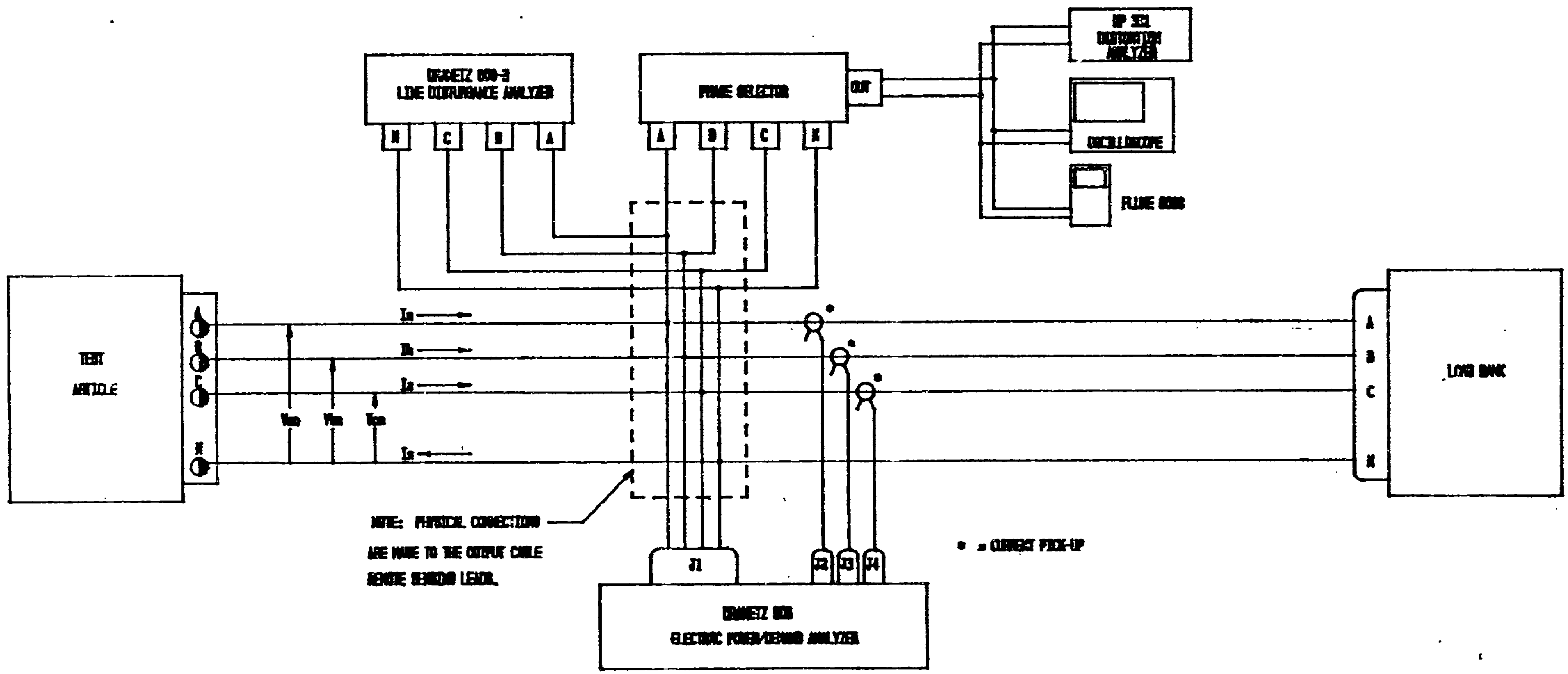


FIGURE1: LOAD BANK TEST INSTRUMENTATION.

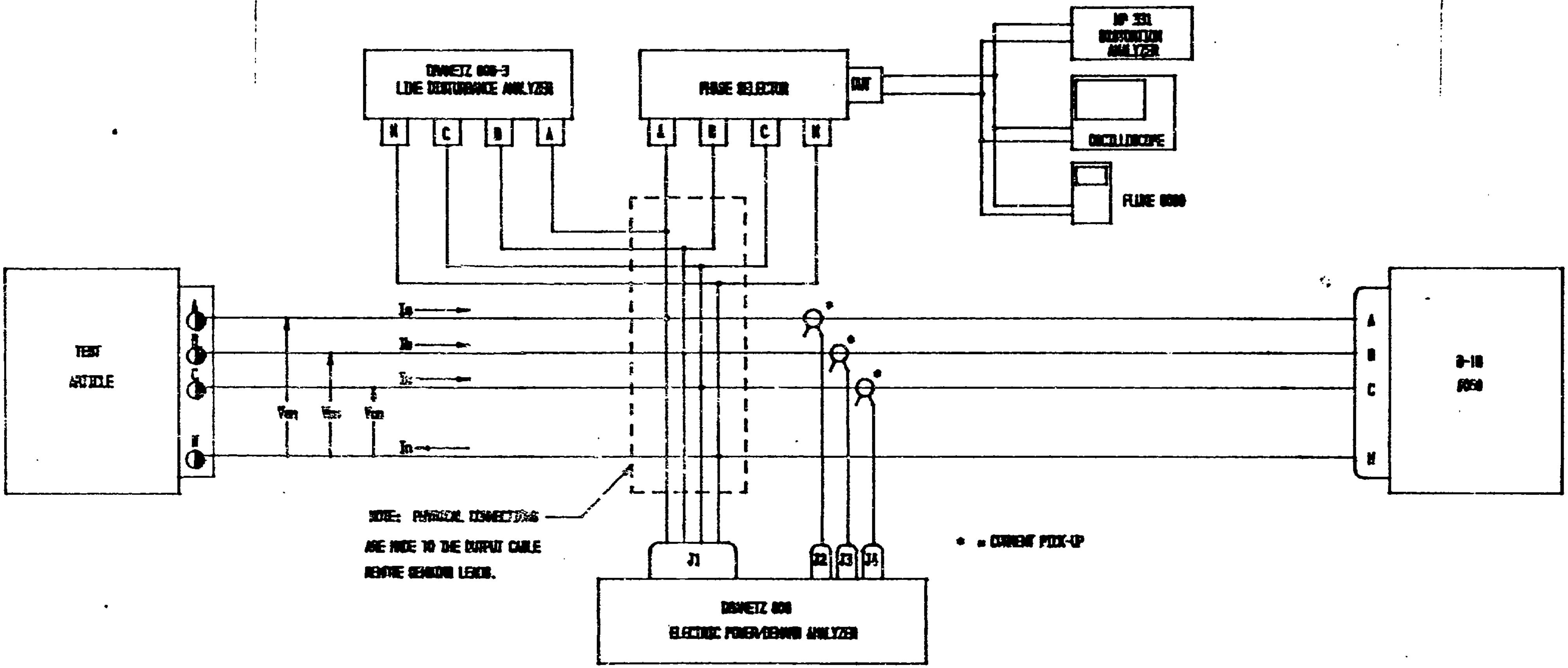


FIGURE 2: AIRCRAFT TEST INSTRUMENTATION

Appendix C

JETWAY SOLID STATE FREQUENCY CONVERTOR

INSTRUMENT	MEASUREMENT	BALANCED THREE PHASE 1.0					BALANCED THREE PHASE 0.80				B PHASE LOAD ONLY 1.0		B PHASE LOAD ONLY 0.8	
		0	25	50	75	100	25	50	75	100	50	100	50	100
Dranetz 808 at the Load	Van	227.7	226.5	226.3	226.8	231.1	223.7	230.4	230.3	232.2	232.9	238.7	231.4	235.7
	Vbn	227.2	226.2	226.1	226.8	230.8	223.8	228.0	229.1	230.6	228.4	226.2	217.4	211.5
	Vcn	227.8	227.1	227.0	227.7	231.8	224.5	231.2	230.8	232.8	234.4	242.9	238.9	247.1
	Ia	0.4326	24.96	50.26	74.77	102.70	31.83	63.25	96.26	114.30	0.4368	0.4762	0.449	0.4647
	Ib	1.646	26.07	50.72	74.98	103.10	30.03	66.14	95.94	118.70	50.87	100.8	62.84	108.3
	Ic	1.612	25.98	50.63	75.25	103.00	31.77	65.64	96.25	118.10	1.681	1.825	1.751	1.859
	AO (KVA)	0.09855	5.68	11.43	16.96	23.85	7.12	14.57	22.17	26.55	0.1017	0.1136	0.1039	0.1095
	BO (KVA)	0.3741	5.90	11.47	17.01	23.81	6.72	15.08	21.98	27.38	11.65	22.92	13.66	22.92
	CO (KVA)	0.3673	5.94	11.58	17.25	24.11	7.13	15.18	22.22	27.51	0.394	0.4435	0.4185	0.4596
	TOTAL (KVA)	0.8399	17.51	34.48	51.21	71.77	20.97	44.81	66.38	81.44	12.1	23.42	14.17	23.49
	AO (KW)	0.09083	5.67	11.43	16.94	23.85	5.82	11.86	18.28	23.14	0.09244	0.09905	0.09652	0.09899
	BO (KW)	0.3384	5.89	11.46	16.98	23.80	5.74	11.68	18.30	24.43	11.65	22.92	10.63	20.46
	CO (KW)	0.3291	5.94	11.58	17.25	24.11	5.81	12.44	18.39	24.42	0.3565	0.3997	0.3751	0.41
	TOTAL (KW)	0.7584	17.50	34.48	51.18	71.11	17.37	35.98	54.97	72.00	12.1	23.42	11.1	20.97
	AO (KVAR)	0.03823	0.00	0.00	0.79	0.00	4.11	8.47	12.55	13.01	0.04253	0.05577	0.03852	0.04691
	BO (KVAR)	0.1594	0.38	0.50	0.98	0.46	3.50	9.54	12.18	12.37	0	0	8.581	10.33
	CO (KVAR)	0.1632	0.00	0.00	0.00	0.00	4.14	8.70	12.47	12.66	0.1678	0.1921	0.1855	0.2076
	TOTAL (KVAR)	0.3609	0.38	0.50	1.77	0.46	11.74	26.71	37.21	38.05	0.2103	0.2479	8.805	10.59
	AO (PF)	0.92	0.99	0.99	0.99	0.99	0.82	0.81	0.82	0.67	0.91	0.87	0.93	0.90
	BO (PF)	0.90	0.99	0.99	0.99	0.99	0.85	0.77	0.83	0.89	0.99	0.99	0.78	0.89
	CO (PF)	0.90	0.99	0.99	0.99	0.99	0.81	0.82	0.83	0.89	0.90	0.90	0.90	0.69
	TOTAL (PF)	0.90	0.99	0.99	0.99	0.99	0.83	0.80	0.83	0.88	0.99	0.99	0.78	0.89
TOTAL HARMONIC DISTORTION HP-331	THD AO	1.37		1.72	1.90	1.74		1.80		1.90	1.45	1.99	3.40	5.80
	THD BO	1.50		1.83	1.93	1.74		2.15		2.03	1.43	3.08	3.80	5.25
	THD CO	1.10		1.67	1.81	1.74		1.80		1.82	4.00	3.85	2.60	4.00

JETWAY SOLID STATE FREQUENCY CONVERTOR

BALANCED THREE PHASE

INSTRUMENT	MEASUREMENT	1.0					0.80			
		0	25	50	75	100	25	50	75	100
FLUKE 8060	Van INPUT	286.0	284.0	282.0	280.0	278.0	284.0	282.0	280.0	278.0
* INPUT VOLTAGE	Vbn	286.0	284.0	282.0	280.0	278.0	284.0	282.0	280.0	278.0
BASED ON LINEAR	Vcn	286.0	284.0	282.0	280.0	278.0	284.0	282.0	280.0	278.0
DROP FROM MEASUREMENT	Ia INPUT	7.8	54.5	94.8	130.1	160.8	55.8	97.3	127.5	155.9
AT NO LOAD AND FULL	Ib	7.4	51.7	86.2	115.1	151.4	51.0	84.1	117.8	145.1
LOAD.	Ic	7.0	51.1	86.0	121.5	151.5	50.6	89.5	119.8	145.5
	Van OUTPUT	231.2	228.6	228.1	229.0	233.1	225.8	232.3	232.3	234.1
	Vbn	228.8	228.2	227.6	228.1	232.8	225.7	230.0	231.1	232.6
	Vcn	230.0	229.1	228.4	229.0	233.8	226.1	233.2	233.2	234.8
	Ia OUTPUT	0.2	26.6	53.2	79.7	107.8	32.1	67.9	101.0	119.8
	Ib	2.0	27.9	53.7	80.3	108.4	34.2	71.0	100.6	124.7
	Ic	1.7	27.8	53.6	79.8	108.1	34.2	70.4	101.1	124.1
	AO FREQ (Hz)	400.1	400.1	400.1	400.1	400.1	400.1	400.1	400.1	400.1
	BO FREQ (Hz)	400.1	400.1	400.1	400.1	400.1	400.1	400.1	400.1	400.1
	CO FREQ (Hz)	400.1	400.1	400.1	400.1	400.1	400.1	400.1	400.1	400.1
O-SCOPE	Vmax AO	692	686	683	689	701	670	689	695	701
	BO	687	683	681	682	697	670	683	692	698
	CO	681	683	680	682	698	669	689	695	701
	Vmin AO	690	685	680	687	699	669	687	693	699
	BO	685	682	679	679	696	669	680	691	695
	CO	680	681	679	681	696	667	687	693	699

CONTROLLED SYSTEMS SOLID STATE FREQUENCY CONVERTER

		BALANCED THREE PHASE									B PHASE LOAD ONLY			
		1.0					0.80				1.0		0.8	
INSTRUMENT	MEASUREMENT	0	25	50	75	100	25	50	75	100	50	100	50	100
Dranetz 808 at the Load	Van	229.6	228.8	227.3	228.8	228.0	227.7	226.4	223.9	219.5	231.0	232.2	231.9	236.8
	Vbn	229.2	228.5	227.0	228.5	228.2	228.0	223.7	223.5	218.4	218.2	209,7	207.8	195.7
	Vcn	229.2	228.7	227.1	228.8	228.4	226.4	226.5	224.2	220.1	237.2	244.8	245.5	252.8
	Ia	0.4199	25.21	50.43	75.19	102.20	82.58	62.05	93.78	129.80	0.4727	0.5299	0.4408	0.4982
	Ib	1.69	26.33	50.90	75.44	102.20	80.60	65.14	93.87	129.80	48.78	94.18	60.56	116.10
	Ic	1.633	26.29	50.85	75.64	102.40	82.68	63.27	93.17	128.90	1.704	1.705	1.762	1.772
	AO (KVA)	0.09644	5.819	11.56	17.34	23.53	7.419	14.05	20.97	28.52	0.1091	0.123	0.1022	0.1173
	BO (KVA)	0.3876	6.061	11.65	17.37	23.55	6.979	14.57	20.98	28.36	10.67	19.84	12.53	22.78
	CO (KVA)	0.3744	6.045	11.64	17.43	23.60	7.40	14.33	20.89	28.38	0.4043	0.4168	0.4328	0.4477
	TOTAL (KVA)	0.8577	17.91	34.86	52.15	70.69	21.77	42.94	62.85	85.27	11.13	20.30	13.09	23.27
	AO (KW)	0.08062	5.82	11.56	17.34	23.53	6.038	11.53	17.34	24.80	0.08005	0.07783	0.07046	0.06598
	BO (KW)	0.3505	6.061	11.65	17.37	23.55	6.021	11.48	17.67	24.79	10.68	19.84	9.826	19.75
	CO (KW)	0.3336	6.045	11.64	17.43	23.60	5.922	11.89	17.32	24.7	0.3717	0.3884	0.4096	0.4226
	TOTAL (KW)	0.7648	17.92	34.86	52.15	70.69	17.98	34.86	52.34	74.3	11.13	20.30	10.30	20.24
	AO (KVAR)	0.05292	0.00	0.00	0.00	0.00	4.311	8.036	11.8	14.08	0.0742	0.09534	0.07408	0.09706
	BO (KVAR)	0.1653	0.00	0.00	0.00	0.00	3.529	9.039	11.31	13.78	0.00	0.00	7.863	11.25
	CO (KVAR)	0.1699	0.00	0.00	0.00	0.00	4.438	8.003	11.68	13.99	0.159	0.151	0.1399	0.1478
	TOTAL (KVAR)	0.3881	0.00	0.00	0.00	0.00	12.28	25.08	34.79	41.85	0.2332	0.2464	8.077	11.49
	AO (PF)	0.84	0.99	0.99	0.99	0.99	0.81	0.82	0.83	0.87	0.73	0.63	0.69	0.56
ALL POWER FACTORS ARE LAGGING	BO (PF)	0.90	0.99	0.99	0.99	0.99	0.86	0.78	0.84	0.87	0.99	0.99	0.78	0.97
	CO (PF)	0.89	0.99	0.99	0.99	0.99	0.80	0.83	0.83	0.87	0.92	9.93	0.95	0.94
	TOTAL (PF)	0.89	0.99	0.99	0.99	0.99	0.83	0.81	0.83	0.87	0.99	0.99	0.79	0.87
TOTAL HARMONIC DISTORTION HP-331	THD AO	3.60		2.30		4.69		2.30		1.98	3.80	5.30	5.00	5.60
	THD BO	3.45		2.39		4.60		2.30		1.98	3.50	4.00	3.30	3.30
	THD CO	3.30		2.26		4.50		2.40		2.04	3.75	5.80	4.50	? FLUK

CONTROLLED SYSTEMS SOLID STATE FREQUENCY CONVERTER
BALANCED THREE PHASE

INSTRUMENT	MEASUREMENT	1.0					0.80			
		0	25	50	75	100	25	50	75	100
FLUKE 8060	Van INPUT	286	284	282	280	278	284	282	280	278
	Vbn	286	284	282	280	278	284	282	2PJ	278
	Vcn	286	284	282	280	278	284	282	280	278
	Ia INPUT	1.2	55	90.4	138.2	170.7	63.8	102.7	132.2	173.1
	Ib	7.8	61.8	94.3	137.2	167.8	54.9	84.4	112.4	168.8
	Ic	4.3	58.5	87.8	131.8	154.6	49.2	98.9	121.9	146
	Van OUTPUT	231.7	231	229.5	230.9	230.2	229.9	228.4	225.8	221.4
	Vbn	231.4	230.5	229.4	230.6	230.2	230.3	225.7	225.5	220.4
	Vcn	231.3	230.7	230	231.1	230.8	228.5	228.5	226.4	221.9
	Ia OUTPUT	0.37	27.1	54.1	80.4	106.8	35.5	66.6	98.1	136.8
	Ib	1.7	29.1	55.3	81.4	107.2	33.4	70.2	99.3	137
	Ic	1.7	28.2	54.2	80.7	106.8	35.1	68.4	97.9	135.4
	AO FREQ (Hz)	400	400	400	400	400	400	400	400	400
	BO FREQ (Hz)	400	400	400	400	400	400	400	400	400
	CO FREQ (Hz)	400	400	400	400	400	400	400	400	400
O-SCOPE	Vmax AO	735	710	693	704	703	704	690	685	668
	BO	730	720	703	707	701	707	696	683	674
	CO	720	707	702	697	701	695	701	686	671
	Vmin AO	720	694	688	685	688	685	684	676	662
	BO	712	684	688	688	689	689	676	675	656
	CO	703	693	695	688	695	686	691	678	664

ECU-105 MOTOR-GENERATOR

INSTRUMENT	MEASUREMENT	BALANCED THREE PHASE 1.0: 0	25	50	75	100	0.80: 25	50	75	100	B PHASE LOAD ONLY 1.0: 50	100	0.8: 50	100
Dranetz 808 at the Load	Van	227.7	227.6	227.5	227.1	226.9	228.5	227.6	227.4	226.4	227.9	228.2	228.9	228.8
	Vbn	227.9	227.8	227.6	228.0	227.8	228.7	229.4	226.8	227.4	222.3	217.4	217.7	208.5
	Vcn	227.6	227.6	226.9	226.1	227.2	229.2	227.3	227.2	227.7	222.4	217.9	222.9	219.0
	Ia	0.424	25.16	39.70	64.46	89.12	30.88	61.71	75.12	108.60	0.46	0.46	0.49	0.48
	Ib	1.685	26.36	46.06	74.49	90.03	27.64	58.86	76.14	106.10	44.94	83.47	55.67	96.97
	Ic	1.580	26.05	43.73	74.82	89.17	27.79	65.92	77.29	106.10	1.58	1.50	1.53	1.58
	AO (KVA)	0.097	5.78	9.08	14.77	20.44	7.06	14.04	17.08	24.60	0.10	0.11	0.11	0.11
	BO (KVA)	0.384	6.05	10.61	17.10	20.71	6.32	13.50	17.26	24.13	10.03	18.18	12.12	20.22
	CO (KVA)	0.360	5.97	10.01	17.05	20.46	6.97	14.98	17.36	24.17	0.34	0.38	0.34	0.33
	TOTAL (KVA)	0.840	17.80	29.70	48.93	61.61	19.75	42.47	51.91	72.88	10.43	18.59	12.57	20.66
	AO (KW)	0.081	5.78	9.08	14.77	20.44	5.78	11.71	14.58	20.68	0.09	0.09	0.10	0.09
	BO (KW)	0.347	6.05	10.61	17.10	20.71	5.17	11.99	14.52	21.09	10.03	18.19	10.70	17.58
	CO (KW)	0.323	5.98	10.01	17.05	20.46	5.20	12.40	14.74	20.79	0.31	0.31	0.31	0.31
	TOTAL (KW)	0.752	17.80	29.70	48.93	61.61	16.15	36.10	43.85	62.56	10.43	18.59	11.11	17.98
	AO (KVAR)	0.052	0.00	0.00	0.00	0.00	4.05	7.75	8.90	13.32	0.05	0.05	0.05	0.06
	BO (KVAR)	0.164	0.00	0.00	0.00	0.00	3.64	6.21	9.34	11.73	0.00	0.00	5.69	9.98
	CO (KVAR)	0.159	0.00	0.00	0.00	0.00	3.68	8.41	9.55	12.33	0.14	0.12	0.14	0.14
	TOTAL (KVAR)	0.375	0.00	0.00	0.00	0.00	11.36	22.37	27.78	37.39	0.19	0.17	5.88	10.17
	AO (PF)	0.84	0.99	0.99	0.99	0.99	0.82	0.83	0.85	0.84	0.86	0.87	0.89	0.85
	BO (PF)	0.90	0.99	0.99	0.99	0.99	0.82	0.89	0.84	0.87	0.99	0.99	0.88	0.87
	CO (PF)	0.90	0.99	0.99	0.99	0.99	0.82	0.83	0.84	0.86	0.91	0.93	0.91	0.91
	TOTAL (PF)	0.89	0.99	0.99	0.99	0.99	0.82	0.85	0.84	0.86	0.99	0.99	0.88	0.87
TOTAL HARMONIC DISTORTION HP-331	THD AO	0.46		0.43		0.42		0.36		0.33	0.51	0.64	0.51	0.66
	THD BO	0.425		0.42		0.38		0.41		0.37	0.47	0.69	0.47	0.61
	THD CO	0.425		0.43		0.41		0.40		0.36	0.50	0.67	0.56	0.75

ECU [illegible] MOTOR-GENERATOR

BALANCED THREE PHASE

INSTRUMENT	MEASUREMENT	1.0					0.80			
		0	25	50	75	100	25	50	75	100
FLUKE 8060	Van INPUT	286.0	284.0	282.0	280.0	278.0	284.0	282.0	280.0	278.0
	Vbn	286.0	284.0	282.0	280.0	278.0	284.0	282.0	280.0	278.0
	Vcn	286.0	284.0	282.0	280.0	278.0	284.0	282.0	280.0	278.0
	Ia INPUT	8.9	56.9	63.4	80.1	91.9	48.4	66.1	74.5	94.4
	Ib	8.4	59.2	66.7	84.3	96.1	51.9	70.2	78.7	98.6
	Ic	8.5	61.0	67.3	82.9	94.5	52.3	69.0	77.4	96.5
	Van OUTPUT	229.4	229.5	229.4	229.1	228.9	230.3	229.5	229.2	228.2
	Vbn	229.5	229.7	229.5	229.9	229.8	230.7	231.3	228.8	229.3
	Vcn	229.4	229.3	228.7	228.1	229.2	231.1	229.2	229.1	229.6
	Ia OUTPUT	0.1	26.9	42.8	68.9	93.4	33.1	65.8	80.6	114.2
	Ib	1.8	28.2	49.0	79.2	94.1	29.5	62.8	81.6	111.2
	Ic	1.8	27.8	49.6	79.5	93.2	29.6	70.4	82.8	111.2
	A0 FREQ (Hz)	400.0	400.0	400.0	399.9	400.0	400.0	400.0	399.9	399.9
	B0 FREQ (Hz)	400.0	400.0	399.8	399.9	400.0	400.1	399.9	399.9	399.9
	C0 FREQ (Hz)	400.0	400.1	399.8	399.8	400.0	400.1	399.9	399.9	399.9
O-SCOPE	Vmax A0	668	669	669	669	669	672	669	669	667
	B0	667	670	670	673	672	673	676	668	670
	C0	668	668	667	667	670	675	669	669	671
	Vmin A0	667	668	668	668	668	670	669	669	666
	B0	567	669	670	672	671	671	675	667	669
	C0	666	668	667	666	670	673	668	668	670

Appendix D

FIGURE 1: PHASE VOLTAGE IMBALANCE

FOR 1.0 PF LOADS.

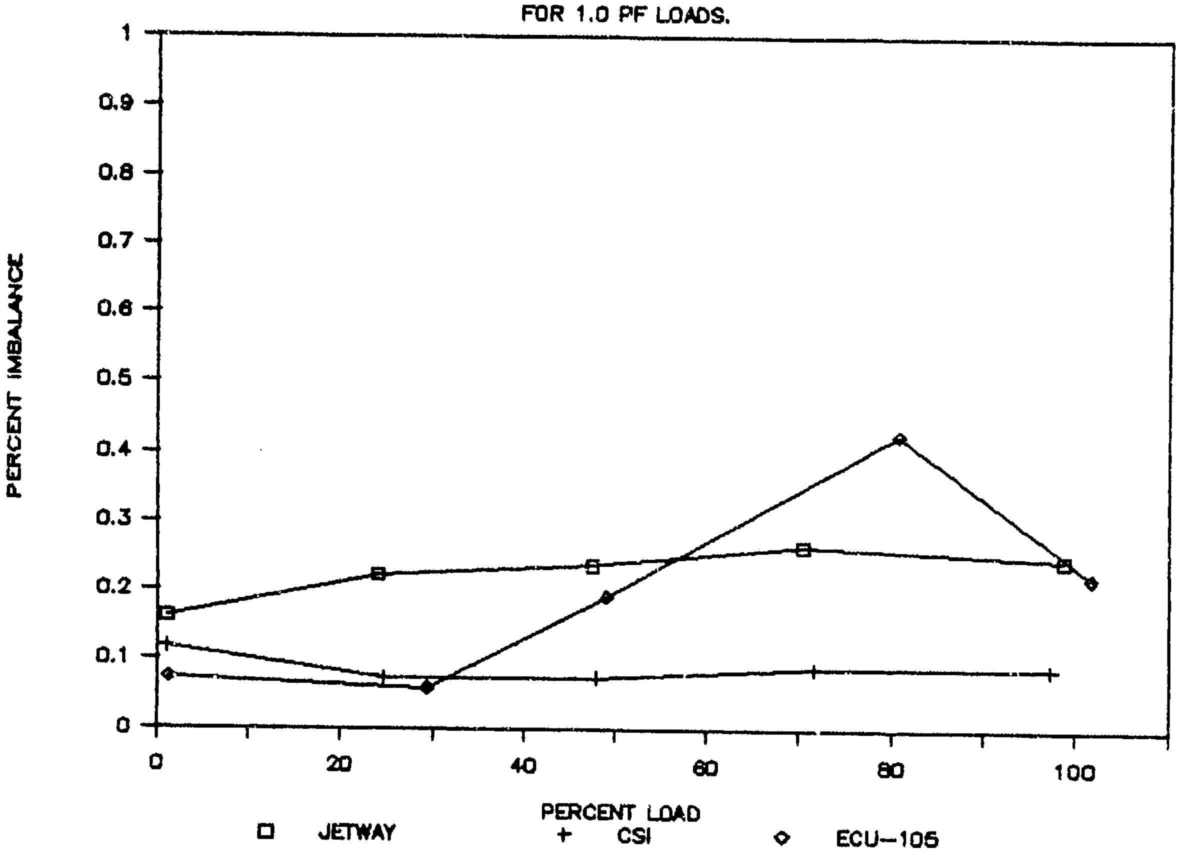


FIGURE 2: PHASE VOLTAGE IMBALANCE

FOR 0.8 PF LOADS.

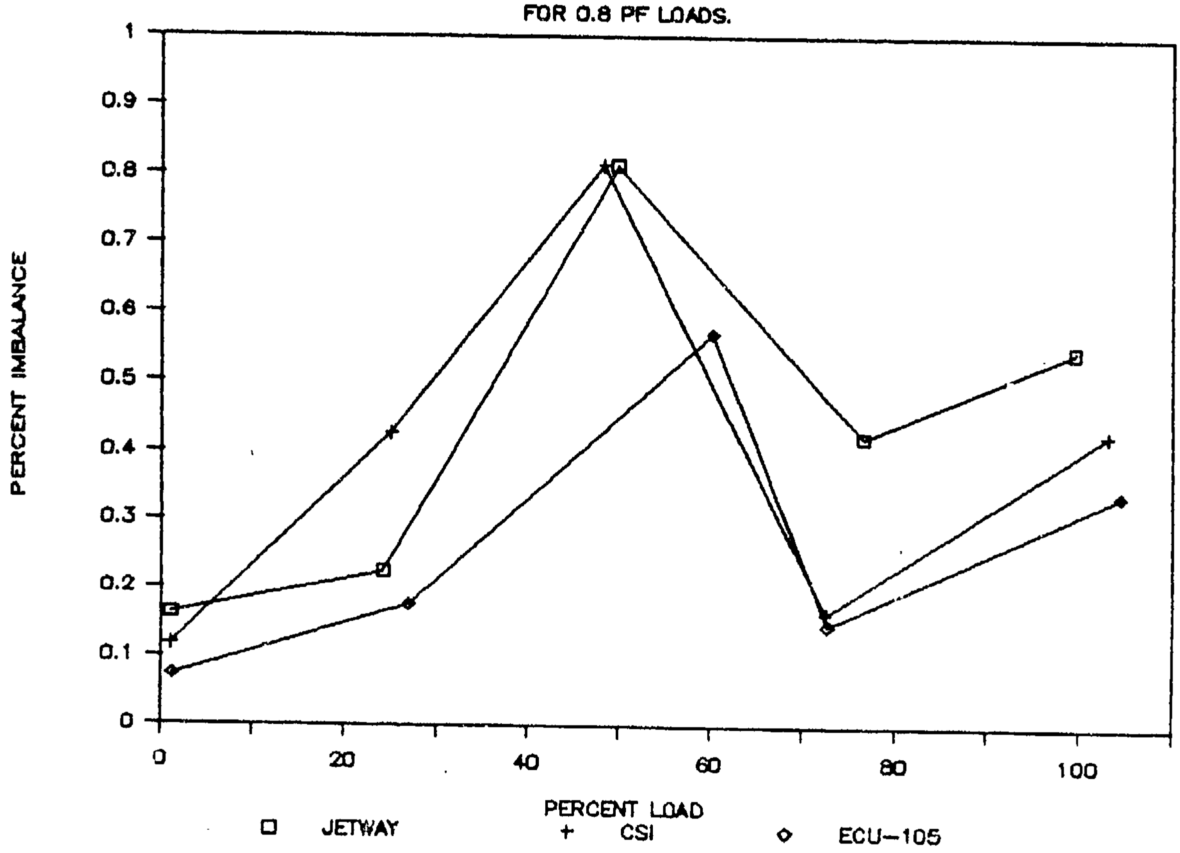


FIGURE 3: VOLTAGE REGULATION

FOR 1.0 PF LOADS.

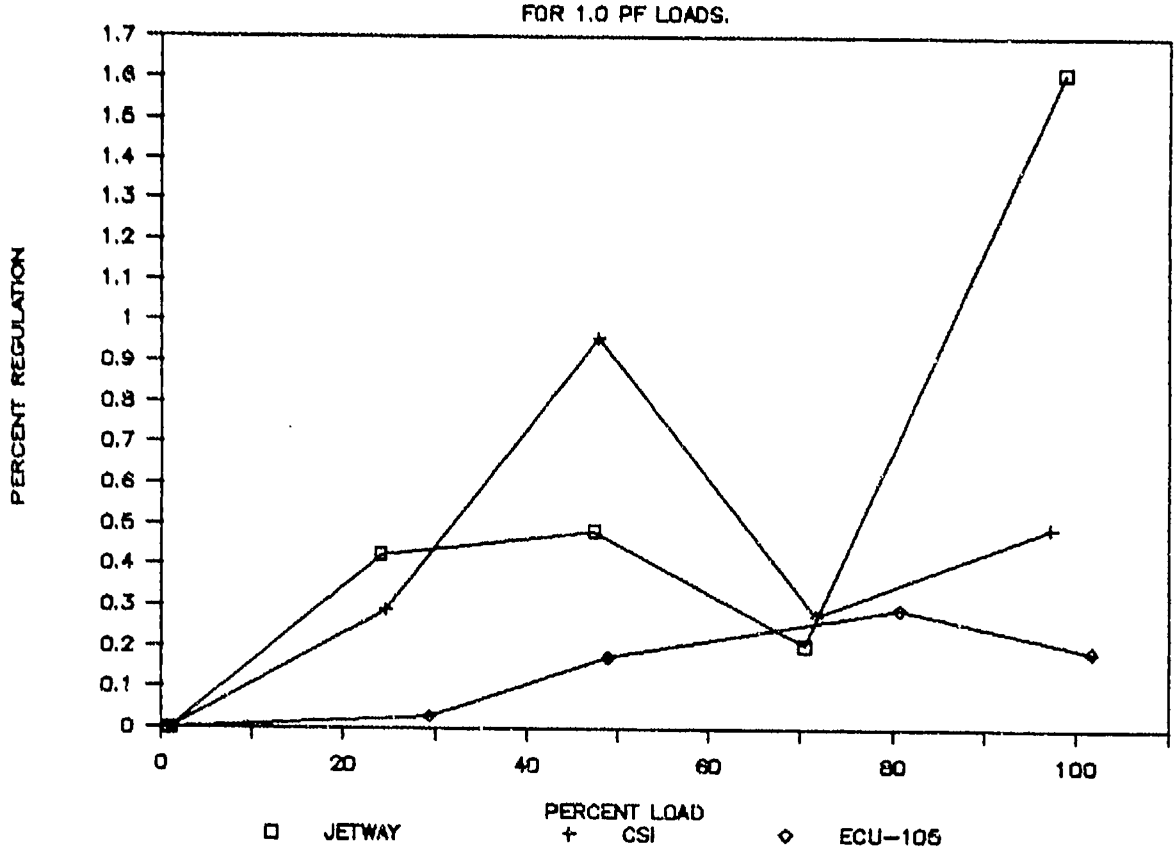


FIGURE 4: VOLTAGE REGULATION

FOR 0.8 PF LOADS.

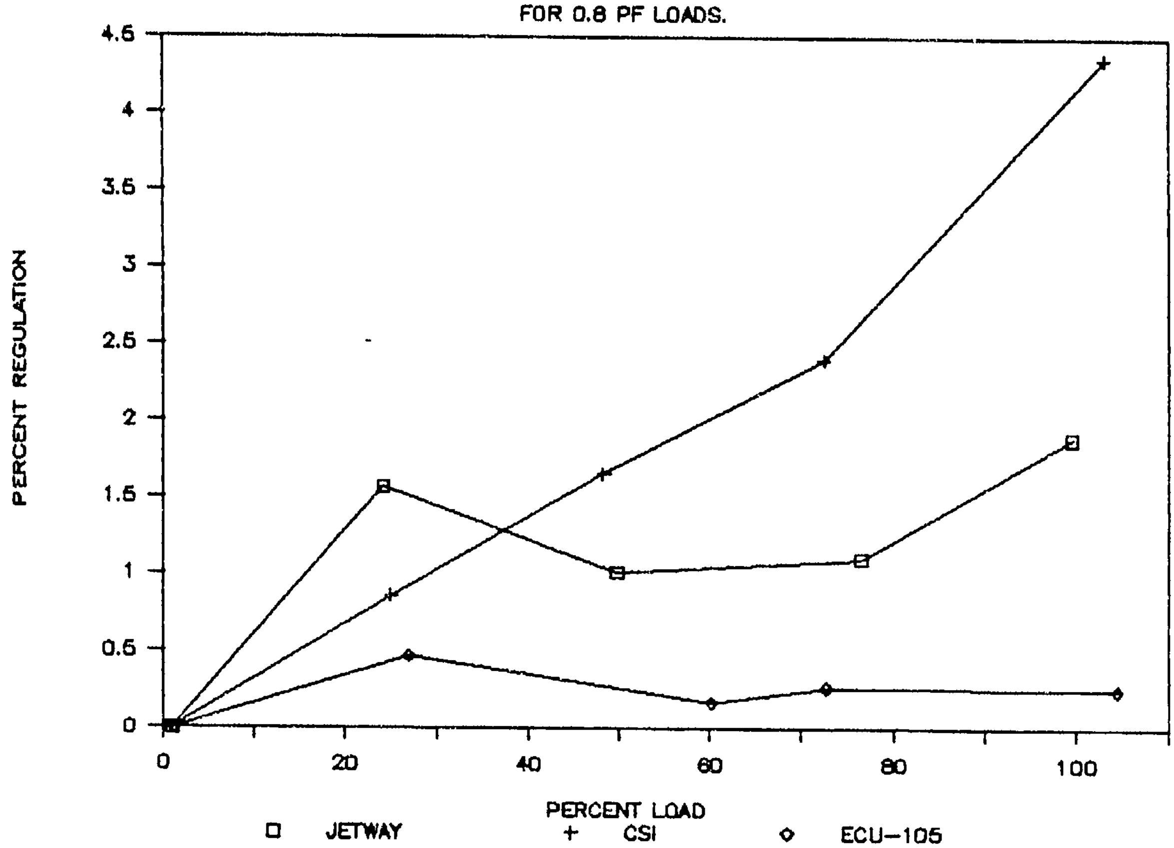
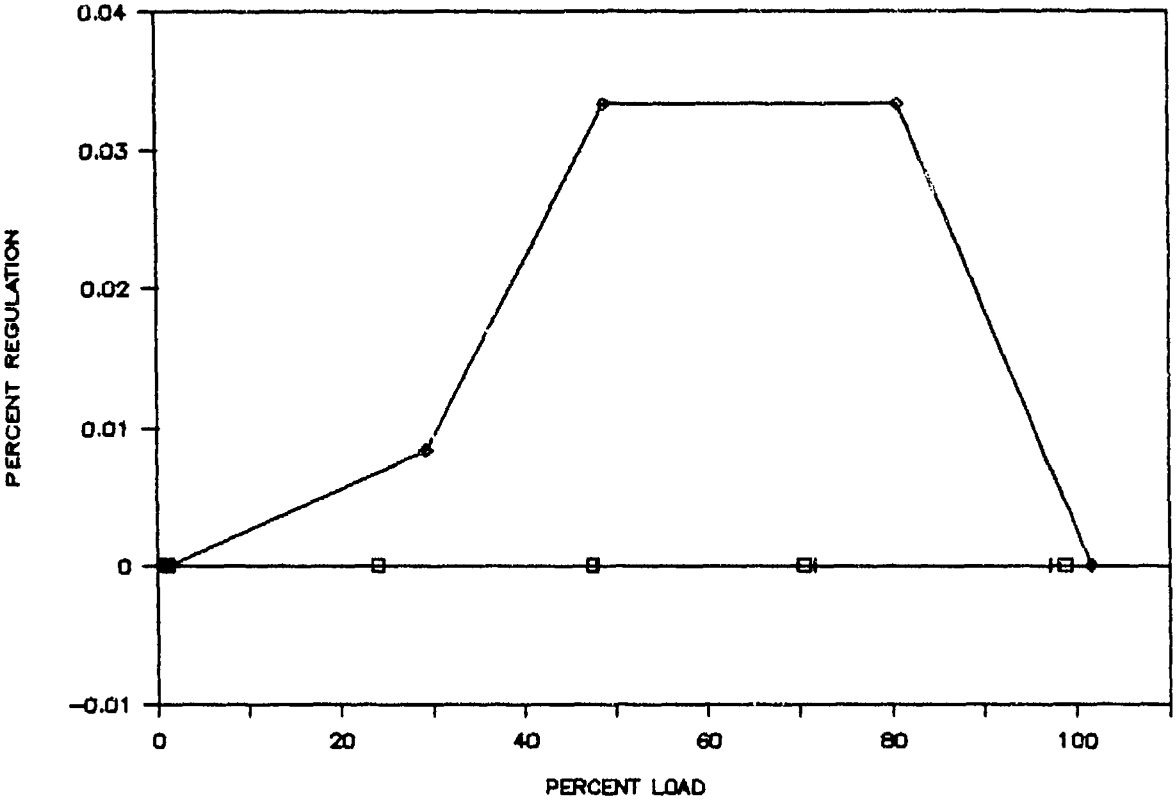


FIGURE 5: FREQUENCY REGULATION

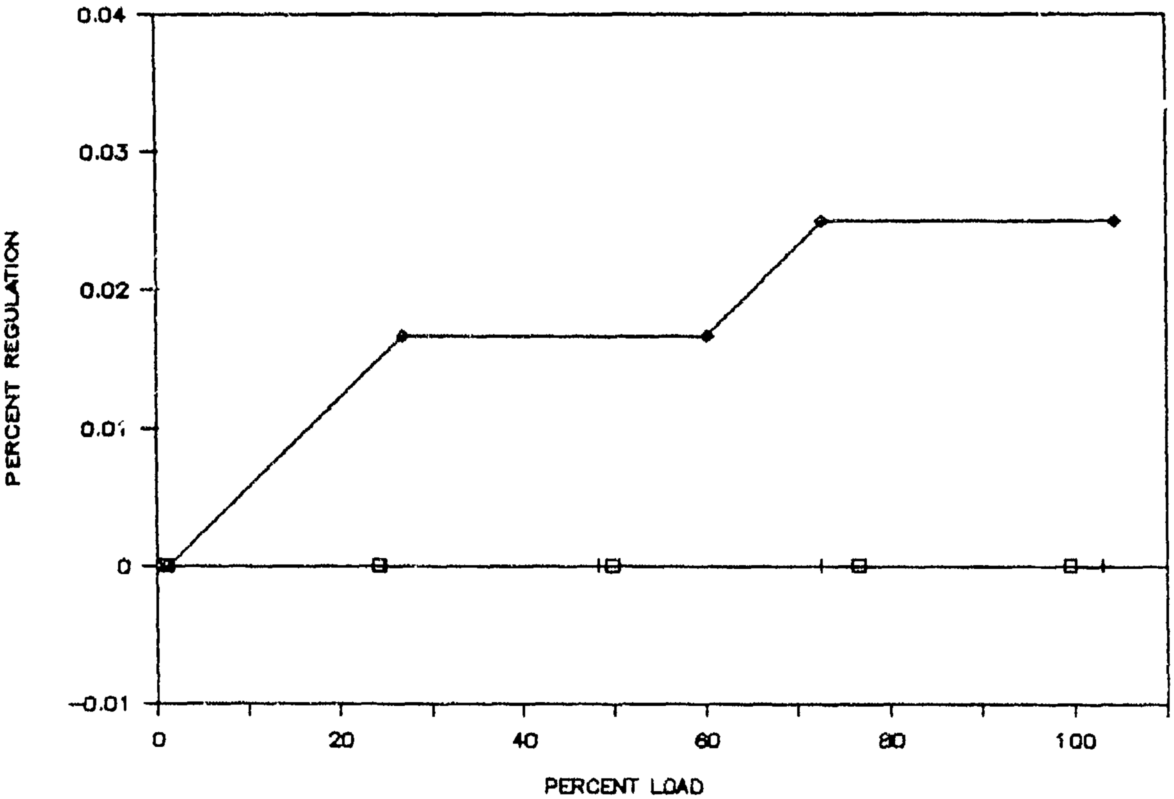
FOR 1.0 PF LOADS.



□ JETWAY + CSI ◇ ECU-105

FIGURE 6: FREQUENCY REGULATION

FOR 0.8 PF LOADS.



□ JETWAY + CSI ◇ ECU-105

FIGURE 7: VOLTAGE MODULATION

FOR 1.0 PF LOADS.

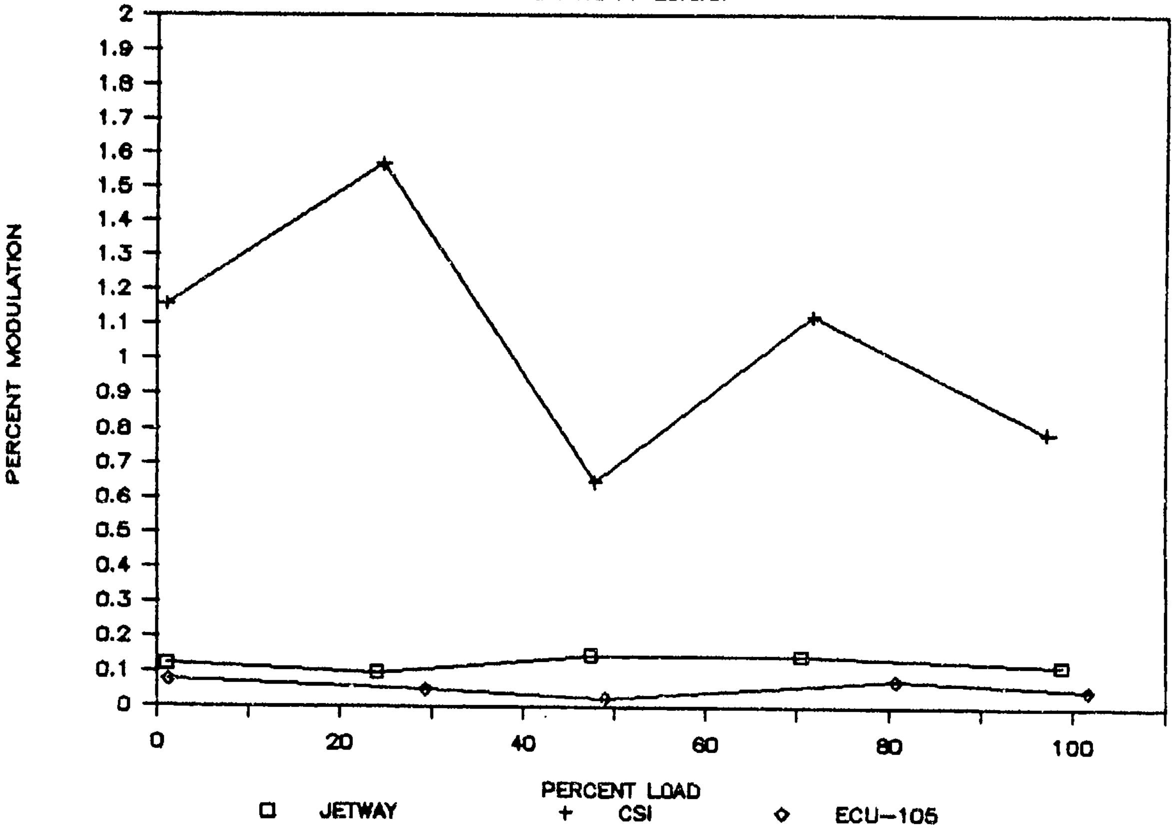


FIGURE 8: VOLTAGE MODULATION

FOR 0.8 PF LOADS.

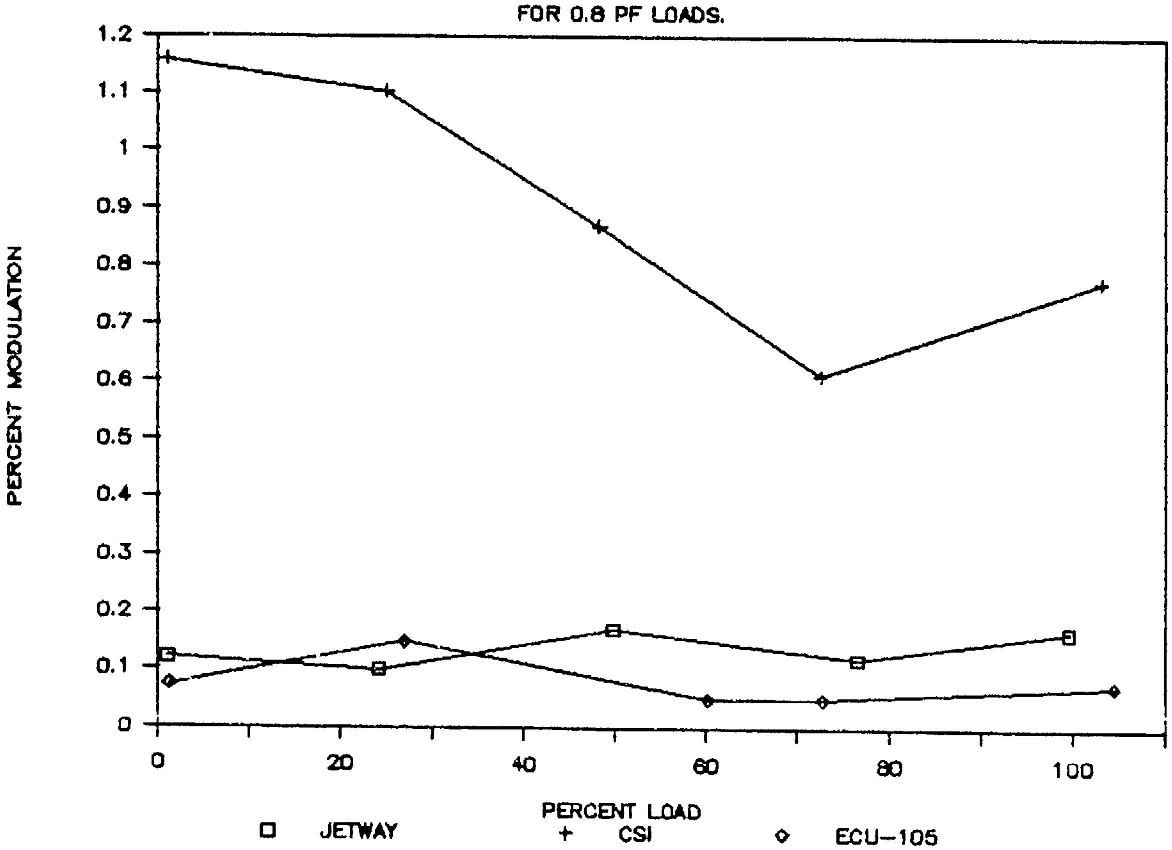


FIGURE 9: TOTAL HARMONIC DISTORTION

FOR 1.0 PF LOADS.

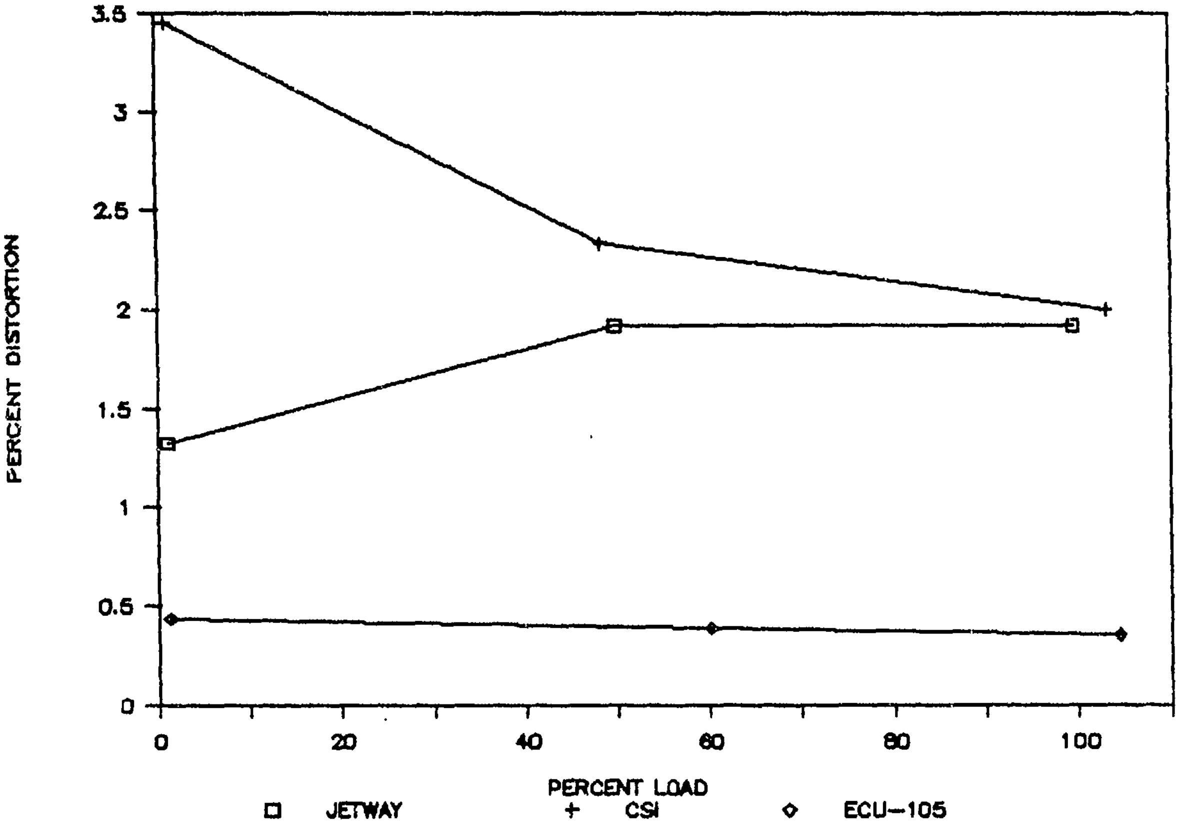


FIGURE 10: TOTAL HARMONIC DISTORTION

FOR 0.8 PF LOADS.

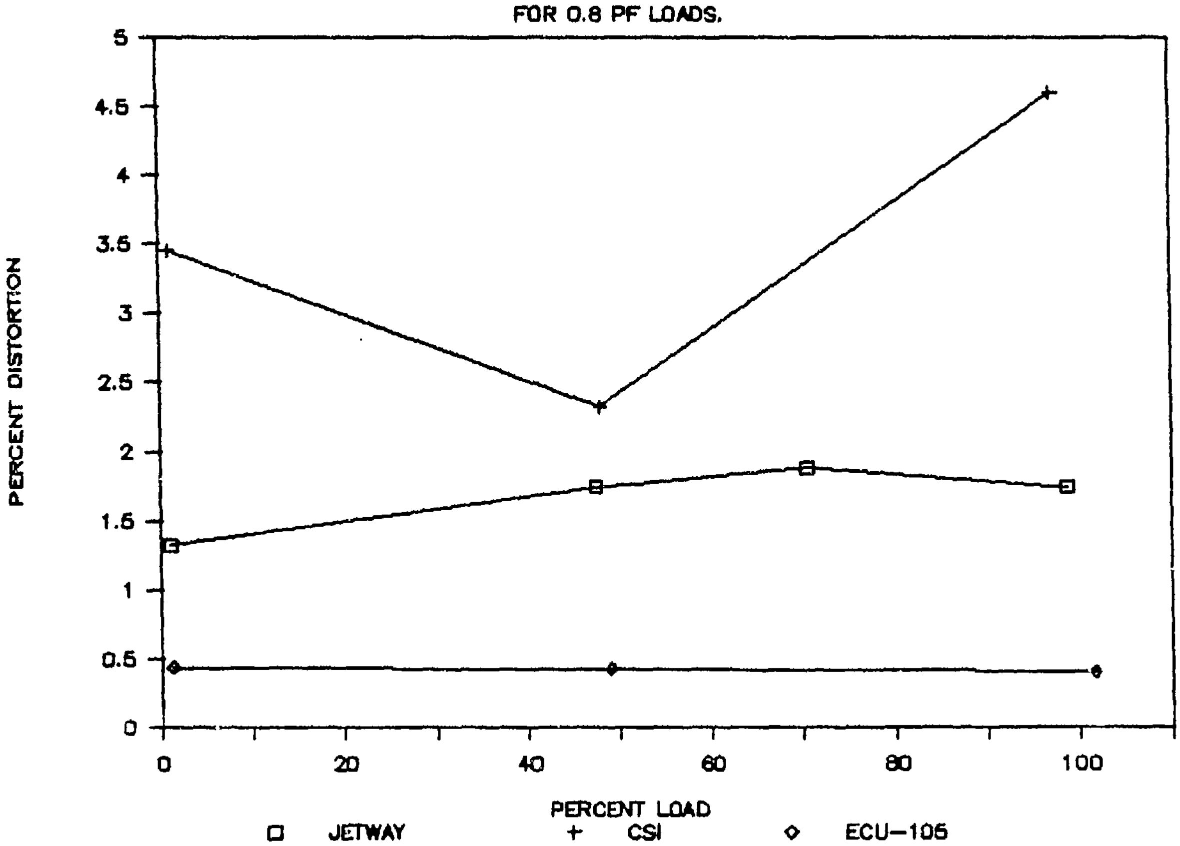


FIGURE 11: VOLTAGE IMBALANCE

FOR SINGLE PHASE, 1.0 PF LOADS.

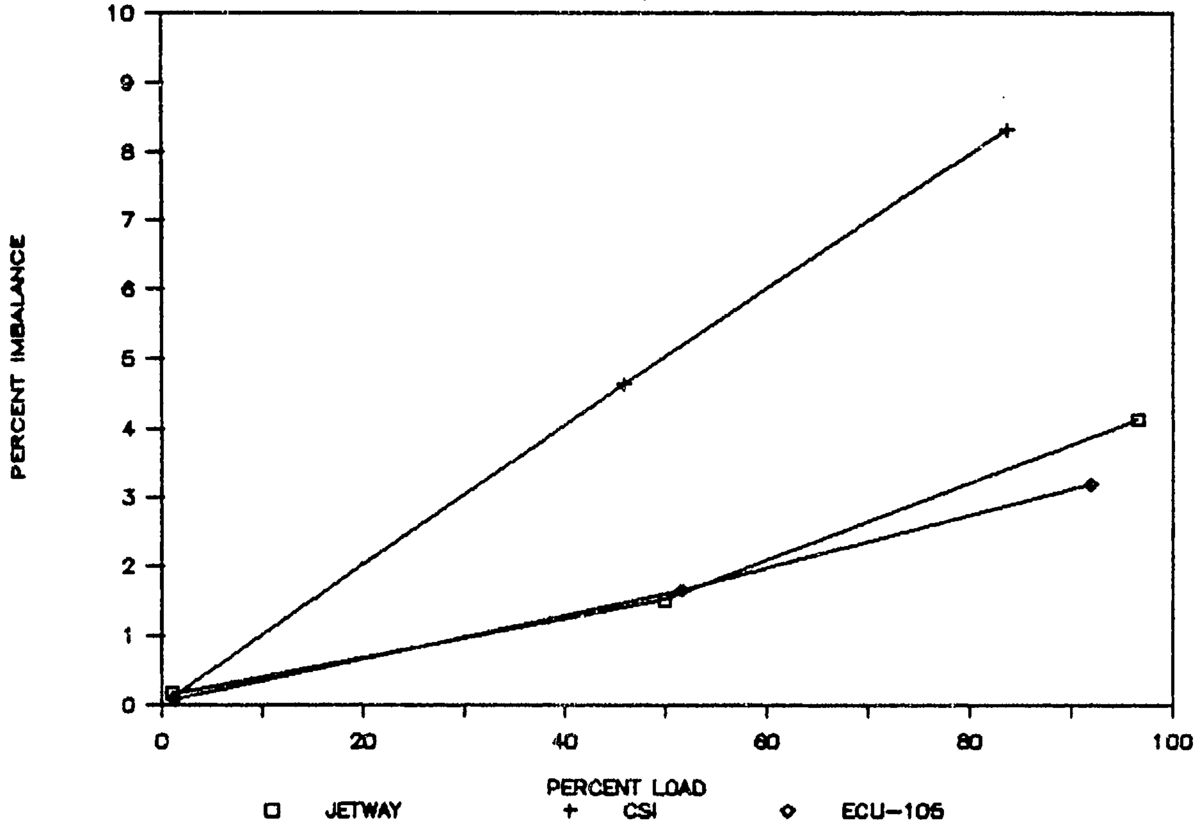


FIGURE 12: VOLTAGE IMBALANCE

FOR SINGLE PHASE, 0.8 PF LOADS.

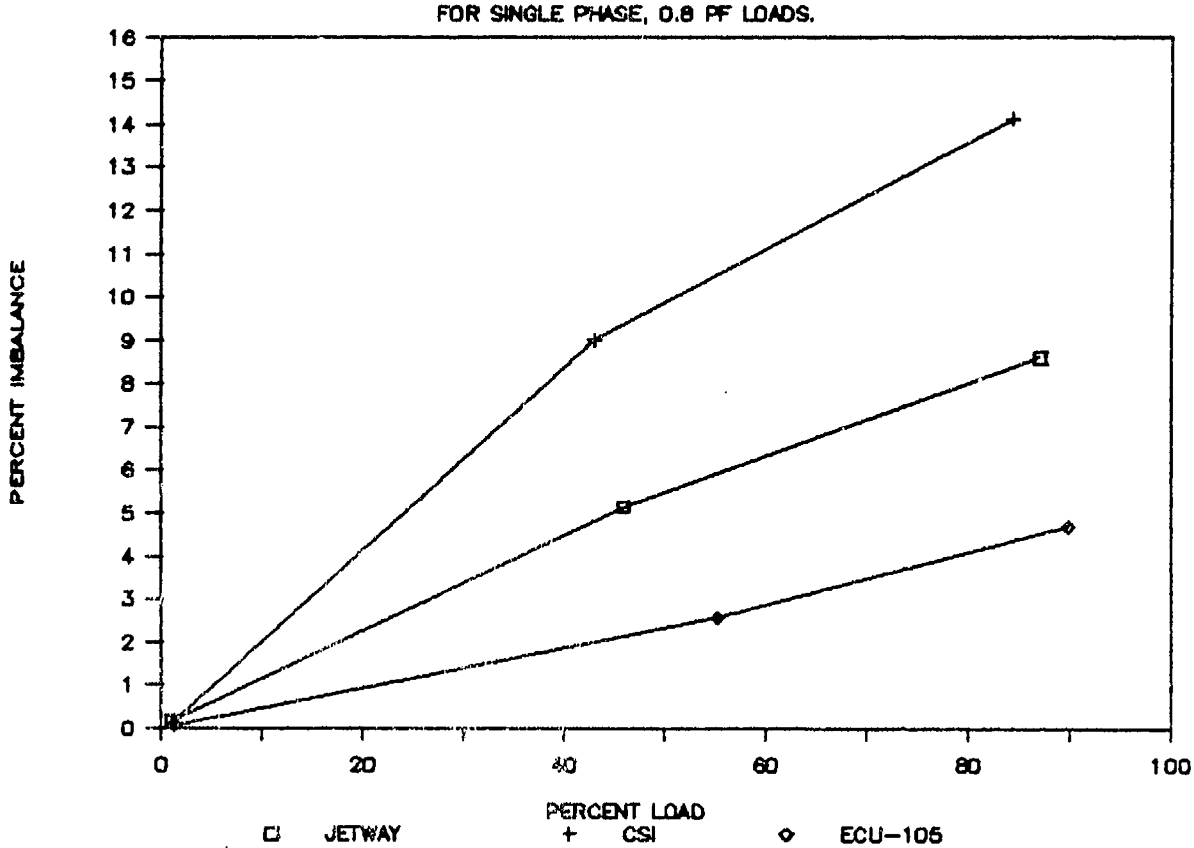


FIGURE 13: VOLTAGE REGULATION

FOR SINGLE PHASE, 1.0 PF LOADS.

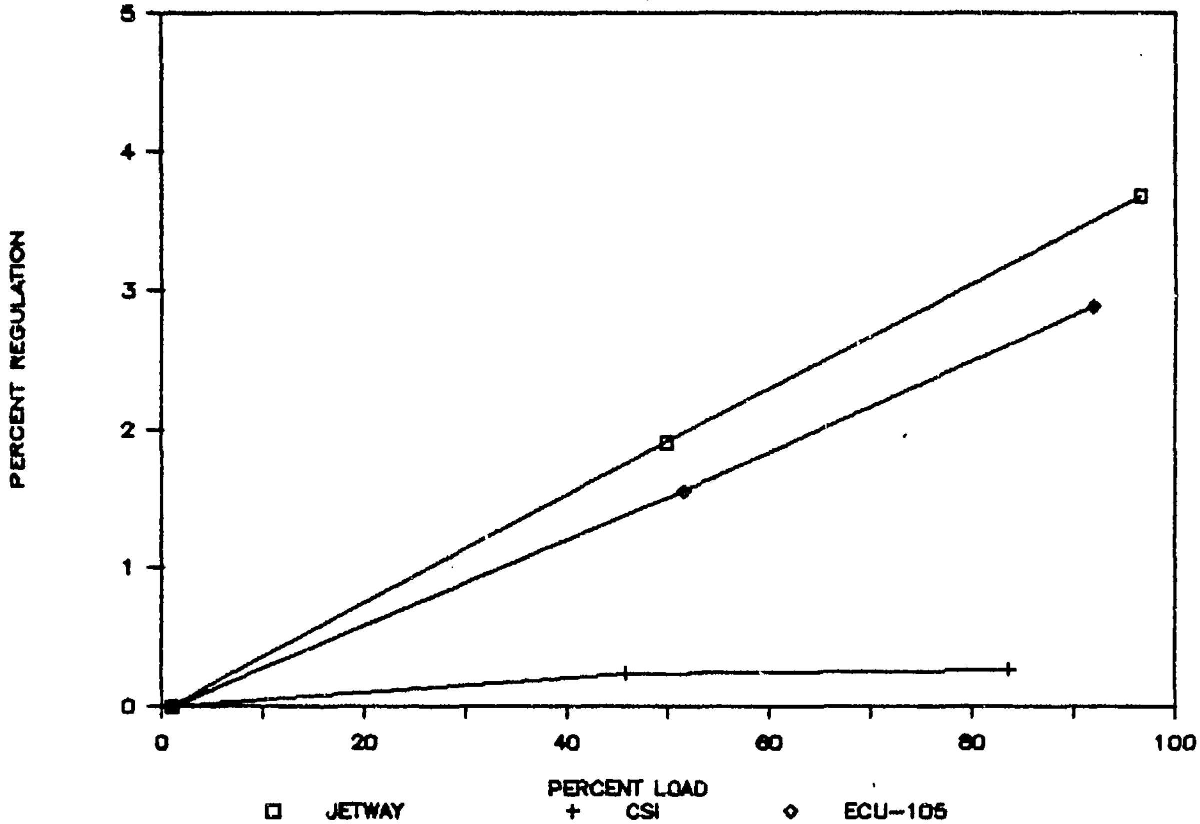


FIGURE 14: VOLTAGE REGULATION

FOR SINGLE PHASE, 0.8 PF LOADS.

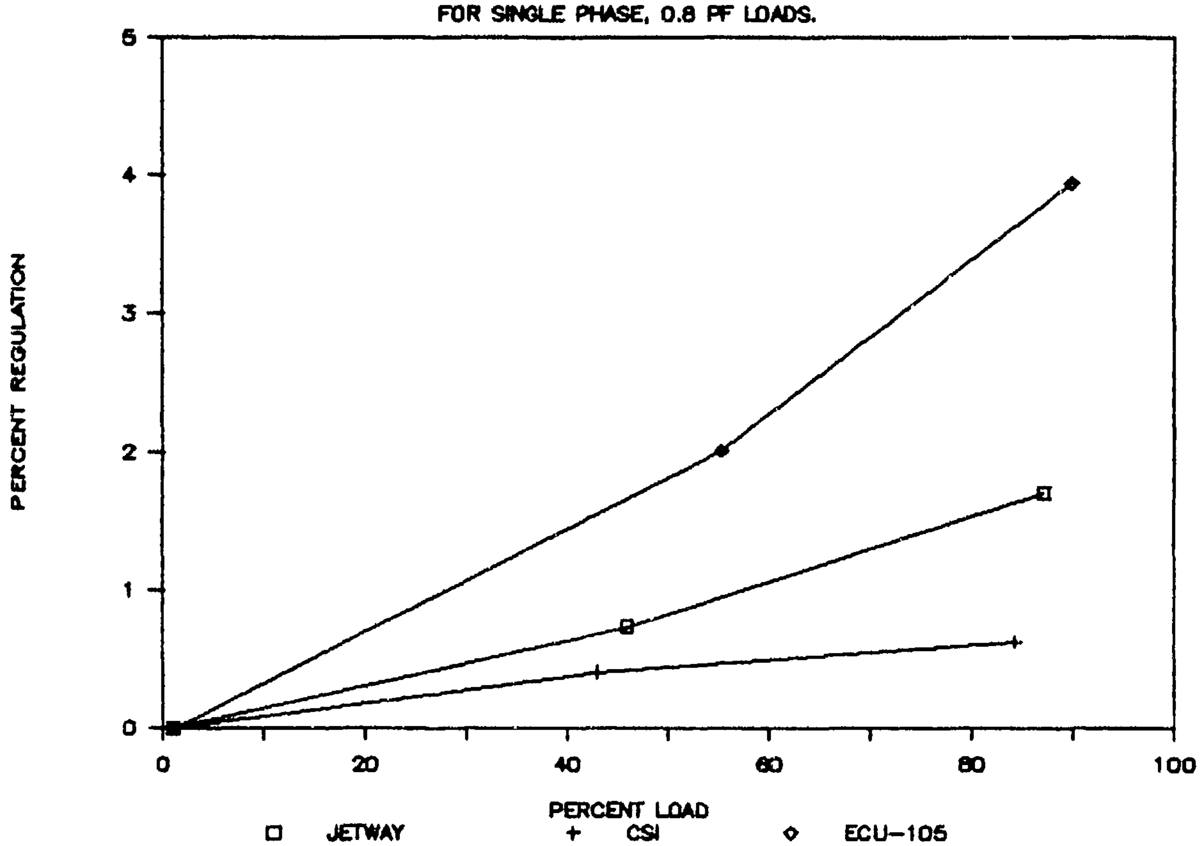


FIGURE 15: TOTAL HARMONIC DISTORTION

FOR SINGLE PHASE, 1.0 PF LOADS.

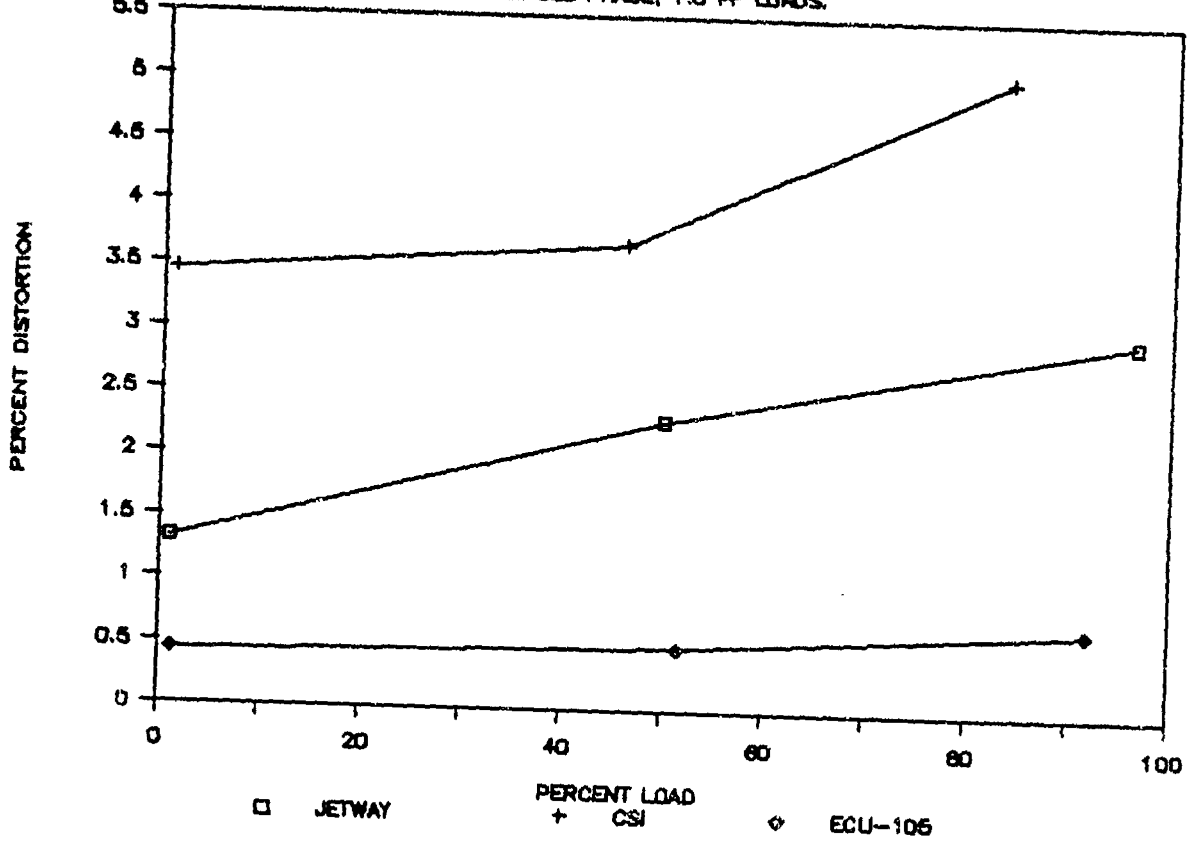
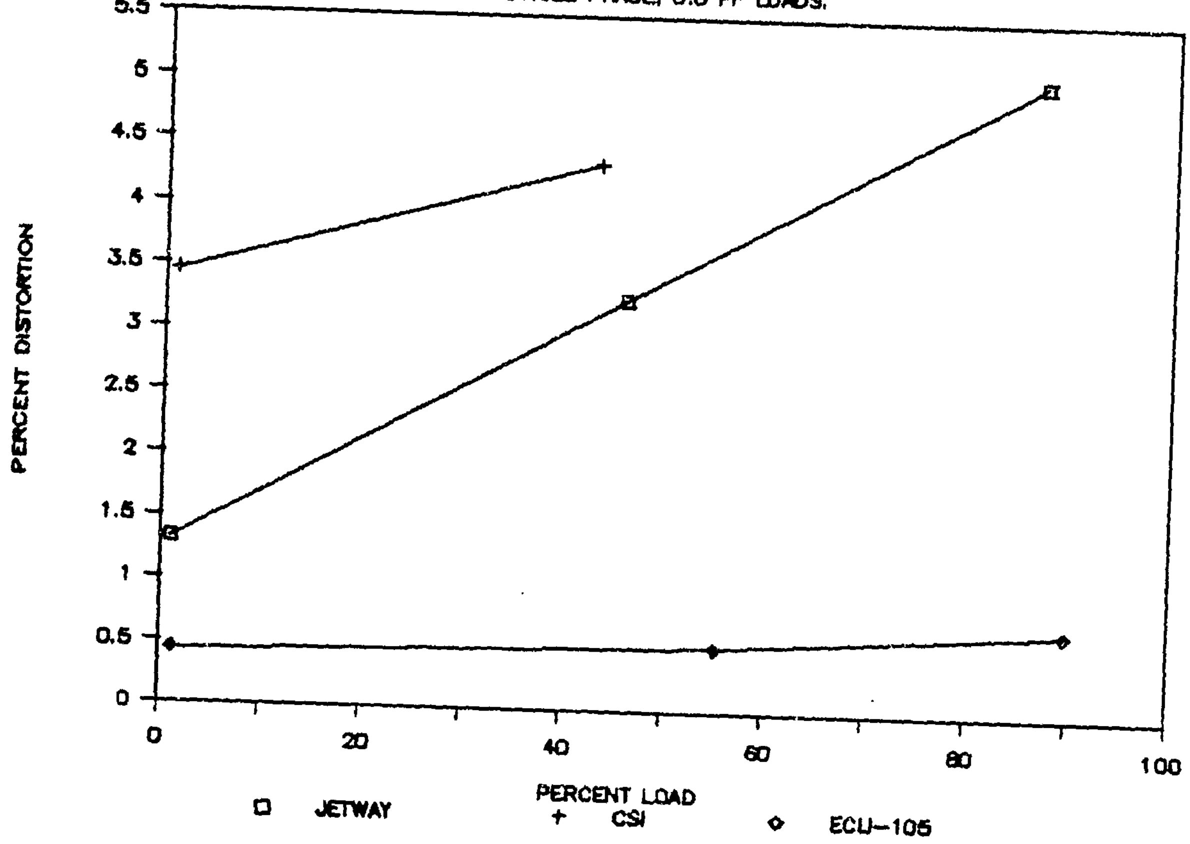


FIGURE 16: TOTAL HARMONIC DISTORTION

FOR SINGLE PHASE, 0.8 PF LOADS.



Appendix E

JETWAY SOLID STATE FREQUENCY CONVERTER

		SHOCK LOAD CONFIGURATIONS			
		1.0		0.8	
INSTRUMENT	MEASUREMENT	50	100	50	100
Dranetz 808 at the Load	Van	226.3	231.6	231.7	232.2
	Vbn	226.1	231.4	230.2	230.6
	Vcn	227.0	232.7	229.4	232.8
	Ia	50.26	103.30	62.81	114.30
	Ib	50.72	103.90	59.10	118.70
	Ic	50.63	103.10	64.57	118.10
	AO (KVA)	11.43	24.05	14.55	26.55
	BO (KVA)	11.47	24.05	13.61	27.38
	CO (KVA)	11.58	24.22	14.81	27.51
	TOTAL (KVA)	34.48	72.33	42.92	81.44
	AO (KW)	11.43	24.05	11.98	23.14
	BO (KW)	11.46	24.05	11.98	24.42
	CO (KW)	11.58	24.22	12.14	24.42
	TOTAL (KW)	34.48	72.33	36.11	72.00
	AO (KVAR)	0.00	0.00	8.26	13.01
	BO (KVAR)	0.50	0.06	6.46	12.37
	CO (KVAR)	0.00	0.00	8.48	12.66
	TOTAL (KVAR)	0.50	0.06	23.20	38.05
	AO (PF)	0.99	0.99	0.82	0.87
	BO (PF)	0.99	0.99	0.88	0.89
	CO (PF)	0.99	0.99	0.82	0.89
	TOTAL (PF)	0.99	0.99	0.84	0.88

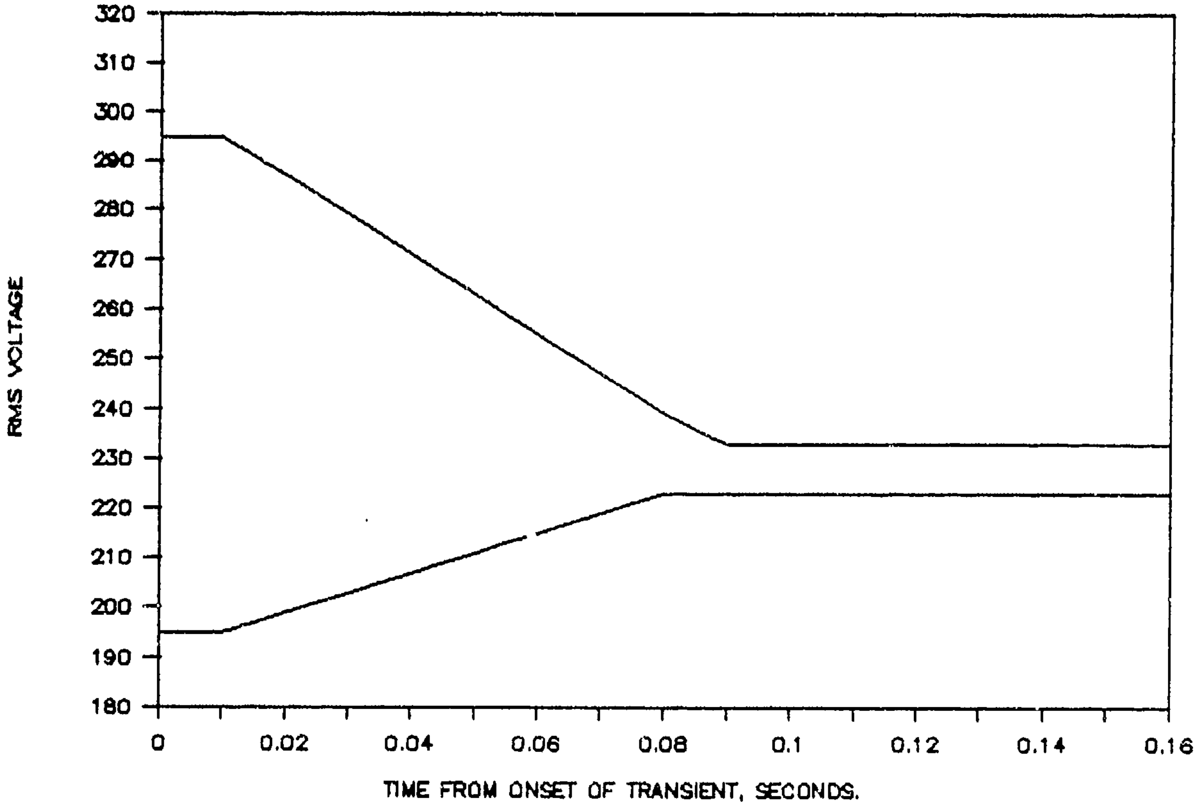
		CSI	SHOCK LOAD CONFIGURATIONS		
		1.0		0.8	
INSTRUMENT	MEASUREMENT	50	100	50	100
Dranetz 808 at the Load	Van	229.0	228.3	227.1	223.6
	Vbn	228.4	228.2	224.1	220.8
	Vcn	229.1	228.9	226.1	221.9
	Ia	50.45	101.80	61.89	129.40
	Ib	51.16	102.00	65.28	131.20
	Ic	50.37	101.10	64.05	130.20
	A0 (KVA)	11.65	23.45	14.05	28.94
	B0 (KVA)	11.78	23.49	14.63	28.99
	C0 (KVA)	11.64	23.35	14.48	28.91
	TOTAL (KVA)	35.07	70.30	43.15	86.84
	A0 (KW)	11.65	23.45	11.67	25.26
	B0 (KW)	11.78	23.49	11.49	25.36
	C0 (KW)	11.64	23.35	11.81	24.93
	TOTAL (KW)	35.08	70.30	34.97	75.97
	A0 (KVAR)	0.00	0.00	7.84	13.35
	B0 (KVAR)	0.00	0.00	9.05	14.05
	C0 (KVAR)	0.00	0.00	8.38	14.64
	TOTAL (KVAR)	0.00	0.00	25.27	42.06
	A0 (PF)	0.99	0.99	0.83	0.89
	B0 (PF)	0.99	0.99	0.79	0.87
	C0 (PF)	0.99	0.99	0.82	0.86
	TOTAL (PF)	0.99	0.99	0.81	0.87

ECU-105 MOTOR-GENERATOR

INSTRUMENT	MEASUREMENT	SHOCK LOAD CONFIGURATIONS 1.0 50	1.0 100	0.8 50	0.8 100
Dranetz 808 at the Load	Van	228.3	227.5	227.7	226.9
	Vbn	228.9	227.4	229.6	223.6
	Vcn	229.8	227.9	230.2	227.6
	Ia	50.15	101.70	61.27	116.30
	Ib	40.06	102.30	49.58	122.40
	Ic	41.42	92.35	54.06	108.00
	AO (KVA)	11.58	23.36	13.95	26.39
	BO (KVA)	9.22	23.49	11.38	27.37
	CO (KVA)	9.57	21.26	12.44	24.60
	TOTAL (KVA)	30.37	68.11	37.79	78.33
	AO (KW)	11.58	23.36	11.63	23.46
	BO (KW)	9.22	23.49	9.54	23.24
	CO (KW)	9.57	21.26	10.32	21.38
	TOTAL (KW)	30.38	68.11	31.50	68.09
	AO (KVAR)	0.00	0.00	7.70	12.09
	BO (KVAR)	0.00	0.00	6.22	14.46
	CO (KVAR)	0.00	0.00	6.94	12.16
	TOTAL (KVAR)	0.00	0.00	20.87	38.71
	AO (PF)	0.99	0.99	0.83	0.89
	BO (PF)	0.99	0.99	0.84	0.85
	CO (PF)	0.99	0.99	0.83	0.87
	TOTAL (PF)	0.99	0.99	0.83	0.87

Appendix F

FIGURE 1. AC VOLTAGE TRANSIENT LIMITS. *



* Derived from MIL-STD-704D, Figure 5.

FIGURE 2. JETWAY TRANSIENT RESPONSE

FOR 1.0 POWER FACTOR SHOCK LOADS.

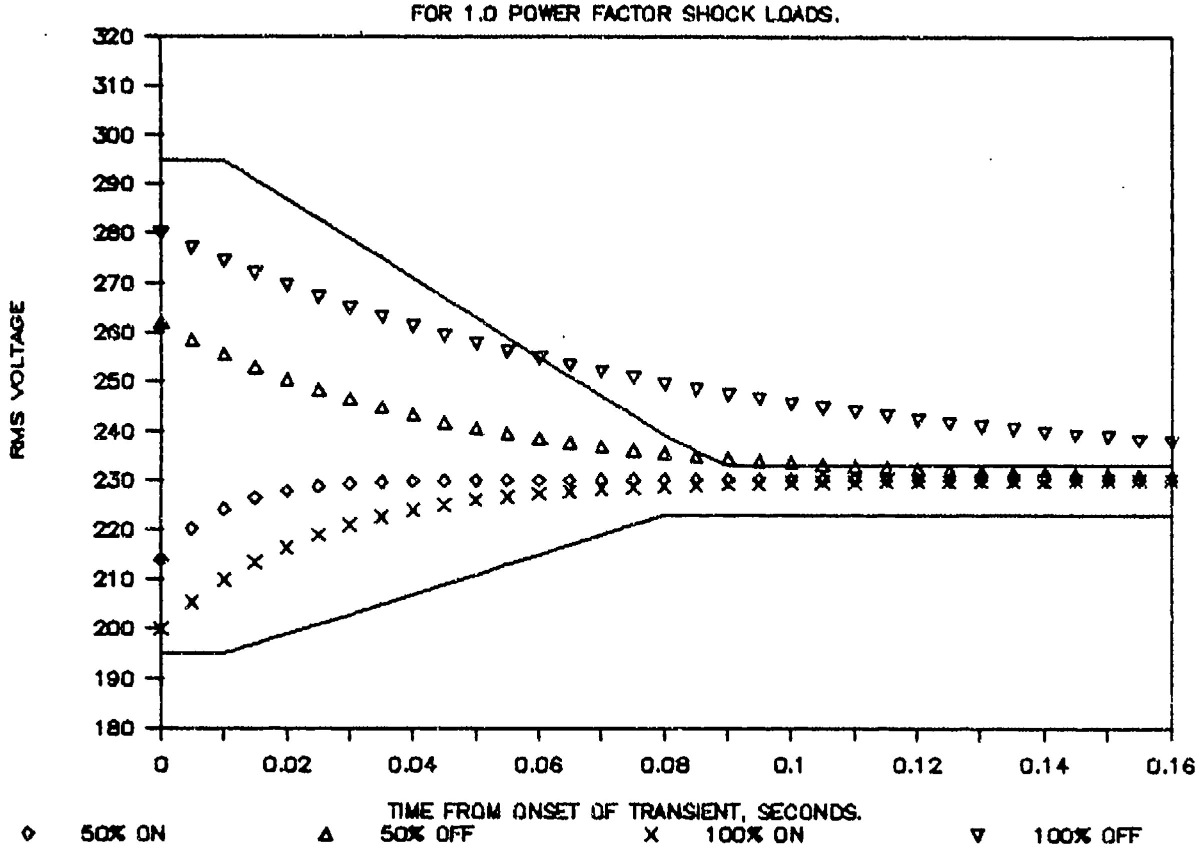


FIGURE 3. JETWAY TRANSIENT RESPONSE

FOR 0.8 POWER FACTOR SHOCK LOADS.

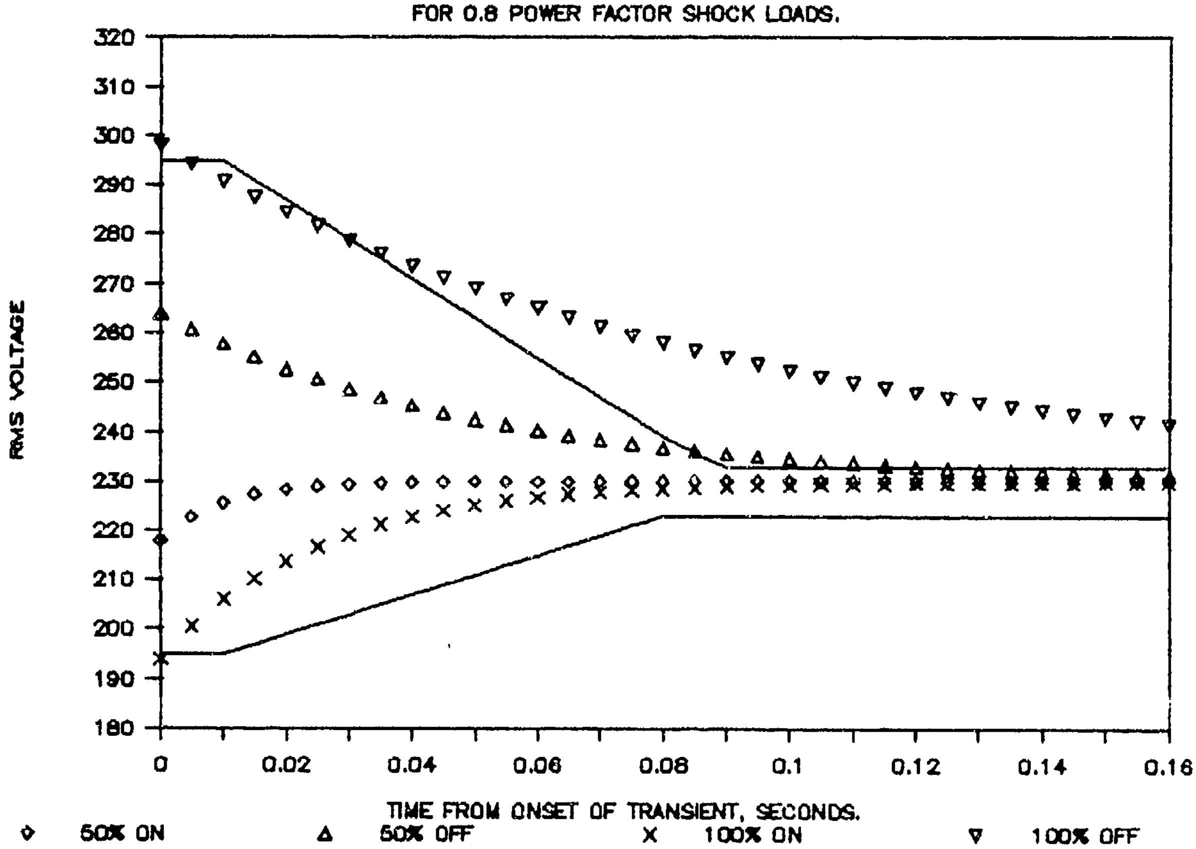


FIGURE 4. CSI TRANSIENT RESPONSE

FOR 1.0 POWER FACTOR SHOCK LOADS.

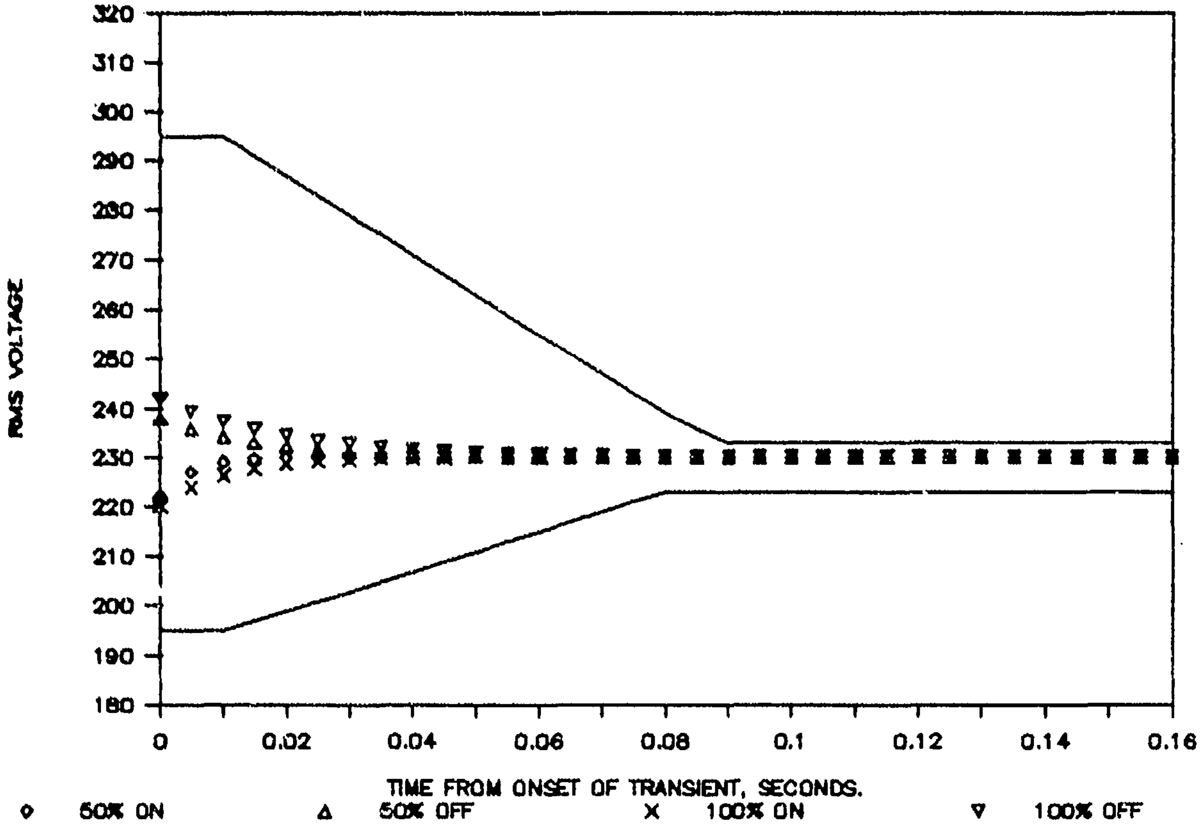


FIGURE 5. CSI TRANSIENT RESPONSE

FOR 0.8 POWER FACTOR SHOCK LOADS.

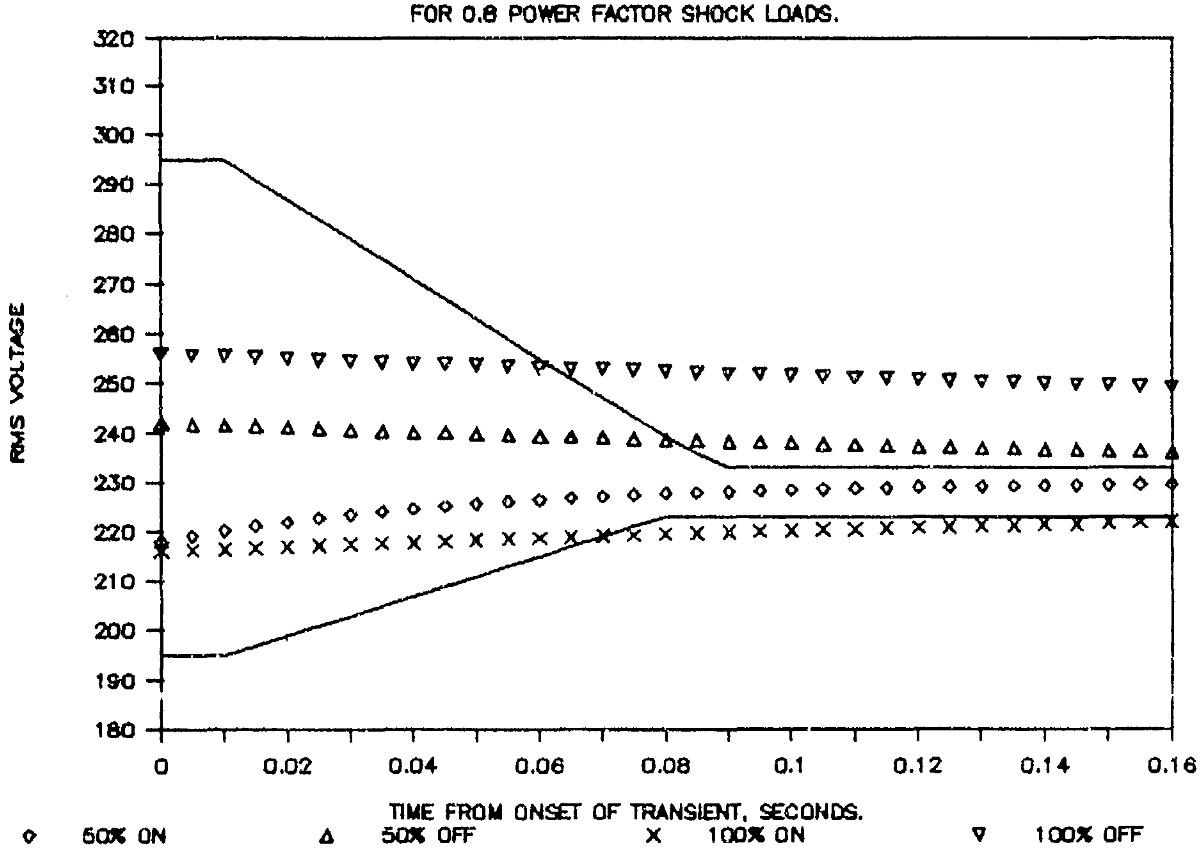


FIGURE 6. ECU-105 TRANSIENT RESPONSE

FOR 1.0 POWER FACTOR SHOCK LOADS.

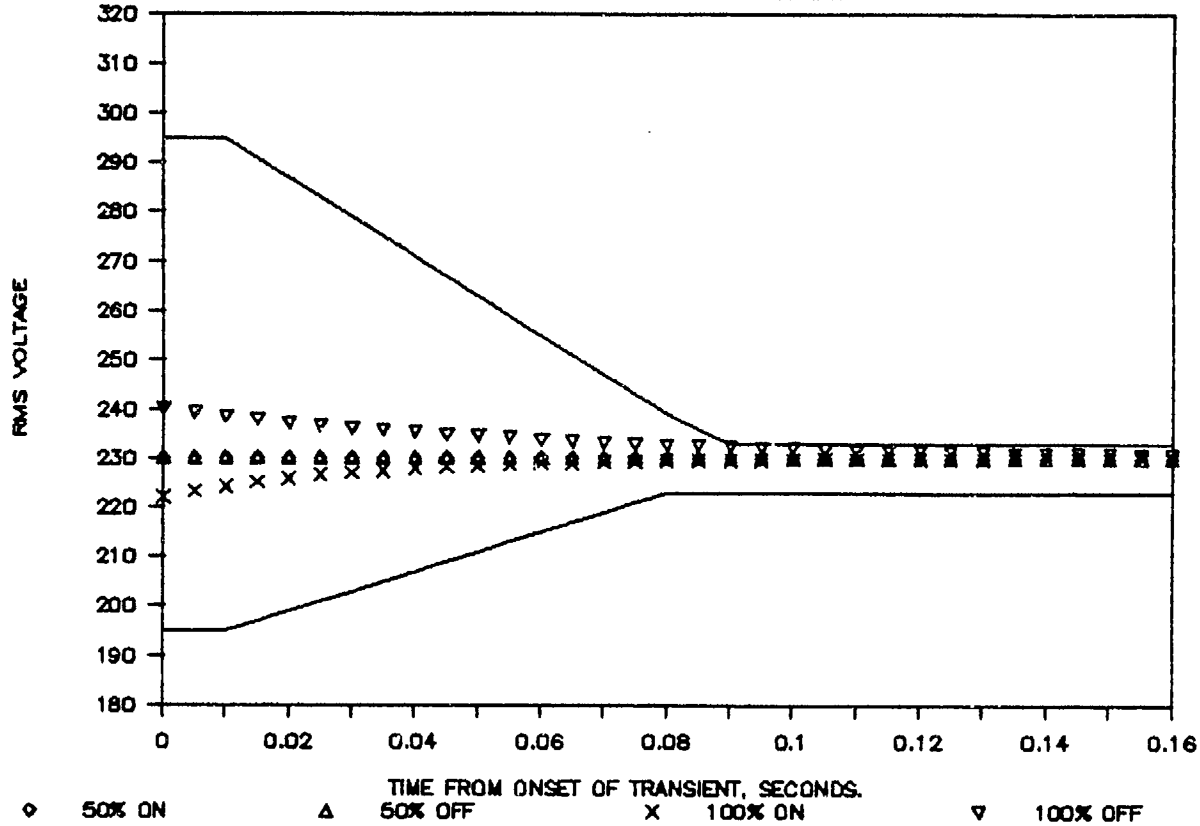


FIGURE 7. ECU-105 TRANSIENT RESPONSE

FOR 0.8 POWER FACTOR SHOCK LOADS.